

AD 740 382

Force-Proportional Reinforcement with
an Application of Spectral Analysis

Stephen C. Fowler

A dissertation presented to the faculty of
Princeton University, in partial fulfillment of the
requirements for the degree of Doctor of Philosophy.

September 1970

Best Available Copy

Table of Contents

	Page
Acknowledgements	ii
Abstract	iii
List of Tables	vi
List of Figures	vii
Chapter 1. Introduction	1
Chapter 2. Continuously Proportional Reinforcement	13
Chapter 3. Force-Proportional Concentration of Sucrose Reward	33
Chapter 4. Some Effects of Gain on Force of Bar Pressing	56
Chapter 5. Feedback during Regularly and Proportionally Reinforced Responding	74
Chapter 6. Summary of Results and Conclusions	125
References	128

Acknowledgements

The author expresses his appreciation for the constant encouragement of his advisor, J. M. Notterman. Special thanks are extended to R. D. L. Fillion, who served as a critical evaluator of ideas and as a source of information concerning the intricacies of electronics. The author is particularly grateful for the patient assistance of Jeanette Koffler.

This research was supported at Princeton University by the Office of Naval Research, Physiological Psychology Branch, under contract NONR 1858(19), J. M. Notterman, Principal Investigator. The work made use of computer facilities supported in part by National Science Foundation Grants NSF-GJ-34 and NSF-GU-3157.

Force-Proportional Reinforcement With
An Application of Spectral Analysis

Stephen C. Fowler

A force-proportional reinforcement schedule specifies the relation between the peak force of a bar press and the amount of reinforcement obtained by such a response. Three experiments were undertaken and detailed statistical analyses (linear regression analysis and spectral analysis) were conducted in order to describe the effects of proportional reinforcement on force of bar pressing. Hungry rats were trained to exert pressure on a silent, isometric manipulandum and were rewarded with sucrose solutions according to a variety of parametric arrangements. Several hundred responses were measured for each of the 66 rats used in the experiments.

Specifically, the research addressed itself to these three questions:

1. Do hungry rats "take advantage" of the force proportional reinforcement contingency by emitting higher forces to obtain greater amounts of reinforcement?
2. Is the ratio of exertion to payoff (specified gain) important in determining the degree to which proportional reinforcement influences response force?
3. Do the sequences of response forces, emitted within a session of responding, display any noteworthy trends or serial

dependencies which might be interpreted as indicating the presence of response - and reinforcement - induced feedback?

In the first experiment, access time to a sucrose solution was made continuously proportional to the force of response. Measurements of lick rate and volume consumed demonstrated that continuous proportional reinforcement was operative. Despite successful implementation of this schedule, the rats displayed no proclivity to press harder to obtain more of the same concentration of sucrose. This latter result was consistent with previous research which used food pellets as reinforcement in discontinuous, step-wise proportional schedules (Notterman & Mintz, 1965; Fillion, Fowler, & Notterman, 1969; Fillion, Fowler, & Notterman, 1970).

In a second experiment force proportional reinforcement was specified by concentration of sucrose so that more forceful bar presses produced sweeter solutions. As a result of exposure to this type of contingency, most rats did learn to respond with greater forces.

A third experiment extended the force-proportional concentration schedule to an examination of the effects of gain on peak force. Within the limits of the parametric conditions used, gain did not appear to be a potent independent variable. Individual differences and "least effort" tendencies may be more important than gain in determining peak force of response.

Data gathered in the second and third experiments were examined by means of linear regression analysis and spectral

analysis. The slopes of the regression lines of peak force on ordinal position did not depart significantly from zero. (From 50 to 100 responses were used in computing the within-session slopes for each of the 49 rats. Spectral analyses were also performed on these data.) Thus linear regression analysis afforded no evidence for "slow" changes in peak force that might have been expected on the basis of learning or drive reduction. Following the lead of Abelson (1953) and using the procedures outlined by Jenkins & Watts (1968), spectral analysis was applied to the session peak force records in order to detect possible serial dependencies that might arise from changes in concentration of sucrose encountered by a rat responding on a proportional reinforcement schedule. The sequences of responses emitted during a session showed only slight departure from randomness, in the sense that the estimated spectral density functions were generally flat. Such non-random effects that did emerge for particular individuals took the form of a high frequency component (.33 to .5 cycles per response), indicating a tendency for peak force to display rapid ups and downs. However, these serial effects were not specific to any particular experimental condition. On the whole, the statistical analyses provided only a modicum of evidence for the presence of within-session feedback effects.

List of Tables

	Page
Table 1. Summary of experiments concerned with the effect of amount of reinforcement on instrumental performance.	8
Table 2. Group means of selected variables for session 20 of Phase II.	28
Table 3. Summary of experimental groups and associated reinforcement contingencies.	34
Table 4. Some parameters of the individual animal force distributions for the initial and final sessions of Phase II.	46
Table 5. Intergroup comparisons by the Method of Planned Comparisons for selected variables for the final three sessions combined of Phase II.	50
Table 6. Summary of experimental groups and associated reinforcement contingencies	59
Table 7. Mean and standard deviation of peak force and number of responses for initial and final sessions of Phase II.	64
Table 8. Regression coefficients of \log_{10} peak force on ordinal position.	83
Table 9. Number of subjects displaying each type of variance change during Phase II.	106

List of Figures

	Page
Figure 1. Amount of reinforcement as a function of required peak force for four schedules of proportional reinforcement.	14
Figure 2. Specified gain as a function of required peak force for the proportional reinforcement schedules given in Fig. 1.	15
Figure 3. Linearity check of apparatus programming access time as a function of peak force.	21
Figure 4. Group mean correlation coefficients of supra-criterion peak force and number of licks as a function of training.	25
Figure 5. Cumulative records of number of licks during each reinforcement interval of session 20 of Phase II.	27
Figure 6. Sketch of reinforcement cup, drawn to actual size.	42
Figure 7. Mean peak force as a function of Phase II training for the four experimental groups.	48
Figure 8. Average amount of sucrose (in milligrams) obtained per response as a function of Phase II conditioning.	51
Figure 9. Average reinforcement rate as a function of Phase II conditioning for the four experimental groups.	52

	Page
Figure 10. Average rate of responding as a function of Phase II training.	53
Figure 11. Mean peak force as a function of the four experimental phases.	63
Figure 12. Average rate of responding as a function of the four experimental phases.	65
Figure 13. Mean peak force for individual subjects as a function of Phase III conditioning.	68
Figure 14. Block diagram depicting three possible feedback loops which may be important avenues of information during a session of bar pressing on a silent, isometric manipulandum.	76
Figure 15. Scatter plot of mean peak force and standard deviation of peak force.	80
Figure 16. Scatter plot of the mean and standard deviation of the \log_{10} transformed peak force distributions for the last three sessions of Phase II.	81
Figure 17. Peak force of response for one session of responding in Phase II.	84
Figure 18. A stochastic process with a slowly oscillating component.	89
Figure 19. Autocorrelation function based on 32 lags. This function was estimated from the data presented in Fig. 18.	91

	Page
Figure 20. Spectral density functions of the cosine plus noise process estimated from the autocorrelation function shown in Fig. 19.	98
Figure 21. Spectral density function with the 95% confidence interval erected about it. The curve labeled "8" is reproduced from Fig. 20.	100
Figure 22. Spectral density functions of the cosine plus noise process estimated from autocorrelation functions which were themselves computed from a series of 160 observations.	102
Figure 23-A. Peak force of response as a function of ordinal position. The data are from the first session of Phase II. This individual was in Group 4 (see chapter 3).	108
Figure 23-B. Autocorrelation function of 16 lags estimated from the data shown in Fig. 23-A.	109
Figure 23-C. Spectral density functions for the data presented in Fig. 23-A.	110
Figure 24-A. Peak force of response as a function of ordinal position for the same subject shown in Figs. 23-A, B, and C. These data were recorded in the second session of Phase II.	111

	Page
Figure 24-B. Autocorrelation function of 16 lags estimated from the data presented in Fig. 24-A.	112
Figure 24-C. Spectral density functions computed from the session peak force data shown in Fig. 24-A.	113
Figure 25-A. Peak force as a function of ordinal position with a session. These data were gathered from an individual in Group 2 during the first session of Phase II.	116
Figure 25-B. Autocorrelation function of 16 lags estimated from the data presented in Fig. 25-A.	117
Figure 25-C. Spectral density functions obtained from the session peak force record shown in Fig. 25-A.	118
Figure 26-A. Peak force as a function of ordinal position for the second session of Phase II. This is the same individual whose data are given in Fig. 25-A.	119
Figure 26-B. Autocorrelation function of 16 lags estimated from the data shown in Fig. 26-A.	120
Figure 26-C. Spectral density functions for a subject of Group 2 estimated from peak force data obtained in the second session of Phase II.	121

Chapter 1

Introduction

Descriptions and theories of instrumental conditioning invariably rest upon the operational definitions used in obtaining the data. Since the appearance of Skinner's definitive work, The Behavior of Organisms (1938), the preponderance of experiments investigating free-operant behavior have defined the response as a momentary closure of a microswitch connected to a spring-loaded bar or lever. The principal datum of these studies has been the time between switch closures, or rate of responding. Other operations yielding other kinds of data are possible, or even desirable as Jaynes (1966) points out. This paper reports on the use of laboratory techniques which emphasize the quantitative nature of both response and reinforcement, and in a manner which departs from the customary analysis of operant behavior.

While investigating response differentiation and generalization, several experimenters (Skinner, 1938; Hays & Woodbury, as reported by Hull, 1943; Arnold, 1945; and Trotter, 1956) became mindful of the need for a more complete account of operant behavior than that afforded by observing response rate. But their attempts to measure force of response (and other dimensions) were hampered by inadequate measuring devices and by limited recording instruments. More recently, advances in electronics have made available sophisticated apparatus appro-

priate for measuring and recording the dimensional properties of the bar-press. Using such equipment Notterman & Mintz (1965) began to explore in detail several quantitative aspects of individual responses emitted under a variety of conditions.

The experiments described in this paper examined a type of reinforcement contingency which Notterman & Mintz (1965) call proportional reinforcement. Proportional reinforcement means that the delivery of a particular quantity of reinforcement is made contingent upon the intensity of a selected response dimension. For example, one of the proportional reinforcement "schedules" used in the present work provides hungry rats with sucrose solutions which increase in percent concentration in rough proportion to force of a bar-press response. The proportionality between response dimensions (whether force, duration, or time integral of force) and reinforcement quantity (whether amount, concentration, or some other dimension) need not be linear. In order to describe various possible proportional reinforcement schedules, Notterman & Mintz (1965) introduced the term specified gain. Specified gain (or just gain) is obtained by dividing the reinforcement quantity by the response value required to produce that quantity. Thus, for the example given above, the specified gain could be expressed in units of percent by weight of solute in solution/gram of force. (Force is expressed in gram equivalent weights for convenience. The force of 1.0 gram at this geographic location is given by Hodgman

(1960) as 980.178 dynes.) These definitions of proportional reinforcement and gain make it possible to formulate the specific empirical questions to which the present research addresses itself.

1. Do rats "take advantage" of the proportional reinforcement contingency by emitting higher forces to obtain greater quantities of reinforcement? Do they learn to press harder to get more reinforcement per response? And if so, under what circumstances?

2. Is the specified gain of the proportional schedule an important independent variable? That is, does the ratio of exertion to payoff influence force of response?

3. Do the sequences of response forces display any important serial dependencies which might be interpreted as indicating the presence of response- and reinforcement-induced feedback phenomena? Can existing statistical methods be used to describe these supposed feedback effects?

The number of descriptive terms which could be applied to proportional reinforcement are probably as numerous as the various investigators working in the area of conditioning and learning. Therefore, a brief discussion of proportional reinforcement from different points of view serves to establish parallels with related fields of experimentation, and thereby helps place the present research into a larger context.

In one sense, proportional reinforcement defines a type of concurrent schedule (Catania, 1966). That is, different

force levels lead to different quantities of reinforcement, and these multiple contingencies are simultaneously available to the organism. The responding animal can be viewed as being engaged in making choices based on presumably desirable rewards on the one hand and correspondingly taxing responses on the other. In the ordinary concurrent schedule experiment used to study choice behavior, there are two distinct manipulanda, a different reinforcement schedule being operative on each. However, when a single, noiseless, isometric manipulandum is used, as in the present case, the distinctiveness of the multiple reinforcement schedules may become blurred. With a silent, isometric manipulandum the organism must rely on the cutaneous and kinesthetic feedback generated by its responses in order to learn what kind of behavior is experimentally correlated with a particular quality or quantity of reinforcement. Further, since the changes in behavior are to be inferred from the intensive measures of responding (as well as from time rate of responding), the terminology associated with concurrent schedules does not seem to be particularly appropriate for describing and analyzing the present experiments.

Proportional reinforcement can also be cast in an incentive framework (Logan & Wagner, 1965). However, most of the data that are the underpinnings of this kind of theorizing are collected in runway experiments. As defined in these experiments, a response usually requires an appreciable amount of time for

execution. Further, the time between responses may be as much as a minute or longer. Thus for the runway situation it does seem intuitively appealing to conceive of the rat as learning what to "anticipate" in the goal box. The anticipations or anticipatory goal responses become conditioned to successive portions of the runway. The reward conditions of the goal box generalize so as to increase and maintain responding at an appropriate level. On the other hand, in the free-operant situation, "responses" are usually defined in such a manner that they occupy very brief periods of time - intervals so brief as to make the ideas of incentive and anticipatory bar-pressing responses much less appealing.

Proportional reinforcement can be regarded from yet another point-of-view. It represents an experimental parallel to theoretical constructs produced by a "micromolar approach to behavior theory" (Logan, 1956). Essentially, this approach recognizes that different intensities of the same "response" (e.g., a bar press) can actually be regarded as different responses. Thus explanations of behavior can be made in terms of what quantitative sub-classes of a particular "response" were either reinforced or not reinforced (see also Antonitis, 1950). As formulated by Logan, this theoretical approach relies on many Hullian concepts which seem better adapted for explanations of behavior observed in a runway. Though the micromolar approach has been of considerable heuristic value (Logan, 1960),

its terminology will not be adopted here because it does not appear particularly suitable for describing data generated in the free-operant situation.

Finally, if one views reinforcement as a stimulus independently of its drive-related properties (drive reducing, [Hull, 1943] or drive inducing [Sheffield, 1966]), then proportional reinforcement can be seen as a special paradigm for exteroceptive cueing of intensity of bar-press responses (Notterman & Mintz, 1962). Discriminably different values of reinforcement, serve as informative signals telling the organism that particular forces have been emitted. Thus reinforcement associated with specific intensities could improve precision of force emission over and above that attainable when discriminably different reinforcements are not correlated with response force.

Considering proportional reinforcement from these varied points of view demonstrates its relation to methods previously used to study choice behavior (concurrent schedules), incentive (amount of reward as it influences performance and learning), response differentiation, and exteroceptive cueing of response force.

Because the proportional reinforcement contingency emphasizes the quantitative aspects of response and reward, some of its historical antecedents also are to be found in the studies dealing with amount of reinforcement. A brief review of this work, followed by a summary of experiments using proportional

reinforcement procedures, should set the context for the subsequent experimental analysis.

In discussing some of the previous work addressed to the problem of instrumental performance and amount of reinforcement, it is convenient to distinguish between the two types of instrumental learning tasks known as the free-operant and the fixed-operant techniques. In the free-operant situation the organism can emit responses at any time. Thus the typical apparatus for examining free-operant behavior is the Skinner box. On the other hand, behavior in the fixed-operant situation is paced by the experimenter so that the response selected for reinforcement can only be made when the experimenter provides the appropriate stimulating conditions. Thus the straight runway is a representative device for studying fixed-operant behavior. The distinction between these learning tasks is made here, not to arouse theoretical issues, but rather to suggest that the two types of procedures do not always produce the same kinds of relationships between performance and quantity of reinforcement. This conjecture is borne out in the experiments summarized in Table 1 (p. 8).

It is clear from Table 1 that a variety of operations have been used to define amount of reinforcement. For example, amount (mg.), volume (ml. or number of licks), access time (sec.), and concentration (%) are all terms specifying quantity of reinforcement. Furthermore, these quantitative measures are

Table 1

Summary of Experiments Concerned with the Effect of
Amount of Reinforcement on Instrumental Performance

Researchers	FREE-OPERANT (BAR PRESS)			Results
	Independent Variables	Dependent Variables	Prop. R.T.	
Guttman (1953, 1954)	concentration of sucrose and glucose	rate of responding	no	higher concentrations yielded higher rates of responding
Catania (1963)	access time to grain hopper	rate	no	higher rate to longer access time only when concurrent schedules were used
Shettleworth & Nevin (1965)	access time to dry food hopper	rate	no	no entirely consistent relation between absolute rate and absolute magnitude
Collier & Siskel (1959)	concentration of sucrose, reinforcement schedules	rate	no	rate of responding is increasing function of conc.; high conc. is less effective when delivered close together
Collier & Myers (1961)	concentration of sucrose, reinforcement schedule, and volume of reward	rate	no	initial rate of responding is increasing function of volume
Notterman & Mintz (1965)	amount of dry food	force of response	no	response force is decreasing function of amount of reinforcement
DiLollo, Ensminger, & Notterman, (1965)	amount of dry food	force of response	no	response force is decreasing function of amount of reinforcement
Notterman & Mintz (1965)	amount of dry food	force	yes	rats do not press harder to obtain more food
Filion, Fowler & Notterman (1969)	amount of dry food	time integral of response force and rate	yes	rats do not press with more effort to obtain more food

Table 1 (Cont.)

	number of pellets correlated with terminal IRT on FI schedule	terminal IRT and rate of responding	yes	rats learned to wait longer for more pellets
Hendry (1962)	amount of water correlated with terminal IRT in FR schedule	terminal IRT and rate of responding	yes	results unclear: difficult to break up fixed ratio "bursts"
Hendry & Van Toller (1964)				
FIXED-OPERANT (RUNWAY ONLY)				
Grindley (1929-30, as reported by Hull (1943))	# grains boiled rice	running speed	no	speed was increasing function of # grains rice
Crespi (1942)	amount of moistened solid food	running speed	no	group receiving larger amount ran faster
Zeaman (1949)	amount of dry food	running speed	no	group receiving larger amount ran faster
Kraeling (1961)	concentration of sucrose and access time to solution	running speed	no	faster running for higher concentration, effect of concentration overshadows access time or caloric content
Logan (1960)	shock for faster running	running speed	yes (?)	rats continued to run but faster responses disappeared
Brown & Horsefall (1965)	number of dry food pellets	running speed	yes	selective RFT of faster speeds with greater amounts yields faster running as compared to yoked control
Smith & Duffy (1957)	volume of sucrose solution	running speed and % correct choices	no	greater volume produces both faster running and more correct when taste is only reinforcer, hunger is irrelevant

not mutually exclusive: For equal volumes (ml.) of sucrose solution, the amount (mg.) always covaries with concentration (%); or for equal concentrations (%), amount (mg.) can covary with access time (sec.). The "%" designation is the percent by weight of the solute in solution (see Pfaffman, Young, Dethier, Richter, & Stellar, 1954). From the foregoing, it is apparent that amount of reinforcement is not being equated with "degree of reinforcing effect" - a dependent variable.

Inspection of Table 1 suggests that a number of generalizations may be drawn from studies examining quantity of reinforcement. In the runway situation, it has been demonstrated repeatedly that running speed is an increasing function of amount (mg.) of dry food, of volume (ml.) of sucrose solution or of concentration (%) of sucrose solution (Grindley, 1929-30; Crespi, 1942; Zeaman, 1949; Kraeling, 1961; and Smith & Duffy, 1957). Moreover, when the fixed-operant is used, concentration (%) (subjectively, taste) may be relatively more important in determining running speeds than volume (ml.) drunk (Kraeling, 1961). The importance of taste factors in controlling rate of response is very prominent in the free-operant situation (Guttman, 1953; Guttman, 1954; Collier & Siskel, 1959; Collier & Myers, 1961): bar press rates reliably increase as a function of sucrose concentration (%) up to about 32%, depending on the schedule demands. On the other hand, with the free-operant procedure there seems to be no

clear relationship between access time (sec.), which covaries with amount (mg.), and rate of responding (Catania, 1963; Shettleworth & Nevin, 1965). But when the force of the bar-press response is measured as a function of amount (mg.) of reinforcement, one finds that force is a decreasing function of amount (mg.) (DiLollo, Ensminger, & Notterman, 1965; Notterman & Mintz, 1965). Collectively, these studies imply that both amount (mg.) and concentration (%) (or taste factors) reliably influence operant performance, but the nature of the relationships depends on whether or not the fixed- or free-operant procedure is used. Further, when bar-press behavior is being examined, the relation between performance and quantity of reinforcement depends on whether or not rate of responding or force of response is used as the dependent variable.

Listed in Table 1 are six experiments which have been concerned with proportional reinforcement. Here again the nature of the results seems to depend on what kind of procedure is employed. Using the straight runway, Brown & Horsfall (1965) demonstrated that rats proportionally reinforced for running speed ran faster than yoked controls. Likewise, Logan (1960) showed that "punishing" fast runway speeds brought about slower running than that obtained with yoked controls. (It is not entirely clear that this study is really an instance of proportional reinforcement, though it is certainly related.) A similar result was obtained by Fillion, Fowler, & Notterman

(1969) in the bar-pressing situation: Of two groups of rats receiving force-correlated amount of food and probability of shock, the group getting the higher probability of punishment displayed lower forces but continued to respond. In general, however, attempts to get rats to take advantage of proportional reinforcement defined by correlating amount (mg.) of reinforcement with intensity of bar-press behavior, have proved unsuccessful. Neither force proportional reinforcement (mg. of food/gram of force) nor effort proportional reinforcement (mg. of food/gram-sec. of effort) have produced evidence for the selective reinforcement of response intensity (Notterman & Mintz, 1965; and Filion, Fowler, & Notterman, 1970).

In these latter two experiments the organism may have reached an upper limit of optional exertion which probably depended on the interaction of several variables (Filion, Fowler, & Notterman, 1969): 1) the absolute amount (mg.) of reinforcement obtained per response; 2) the specified gain; 3) the choice available of pressing again rather than harder; 4) the capacity of the organism to discriminate changes in reinforcement and changes in motor feedback cues; and 5) certain apparatus limitations may have precluded the rats' taking advantage of the proportional reinforcement. An experimental examination of this last possibility is described in Chapter 2.

The dramatic way in which rate of response is influenced

by sucrose concentration (see Table 1) suggests that the more appropriate procedure for obtaining proportional reinforcement effects is in terms of sweetness (%), rather than in terms of amount (mg.). If, as is pointed out above, failure to obtain an upward shaping of response force was partially the result of the organism's inability to make the necessary discrimination in amount (mg.) of reinforcement, then the use of concentration to define reinforcement quantity should provide a better opportunity for proportional reinforcement to become operative. This approach is explored in Chapter 3.

The research reported in Chapter 4 extends the procedures developed in Chapter 3, and examines the importance of specified gain as an independent variable.

In Chapter 5 detailed statistical analyses are undertaken. This endeavor relies heavily on a type of time series analysis known as spectral analysis. A discussion of this method along with a rationale for its use is given in Chapter 5. Suffice it to say at this point that previous research (Mintz, 1962) has indicated that fairly robust sequential effects do develop in peak force of response during some types of fixed-ratio responding. Further, one might expect "contrast effects" (Reynolds, 1961) to develop when the organism experiences changes in amount (mg.) or sweetness (%) of reward during a series of bar-pressing responses.

Chapter 2

Continuously Proportional Reinforcement

As noted earlier, Notterman & Mintz (1965) have reported that rats do not seem to take advantage of force proportional reinforcement by pressing harder to obtain more reinforcement per response. This result may have been dictated by certain apparatus-related discontinuities in reinforcement availability. The purpose of this chapter is to describe an experimental technique which removes the discontinuities and, in turn, provides the organism with a continuously force-proportional reinforcement schedule.

Figure 1 shows some of the values of quantity of reinforcement which were actually used in Notterman & Mintz's experiment. In Fig. 2 are depicted some of the specified gain values for the same study. The reason for the marked lack of continuity in both quantity of reinforcement and specified gain lies in the fact that force was quantized into steps, and the smallest increment in reinforcement per step was 20 mg. Further, the maximum number of steps was limited to five, thereby setting an upper bound on quantity of reinforcement per response and also creating a situation such that above the highest force-reinforcement step, specified gain varied inversely with response force. Whether these discontinuities were of sufficient magnitude to nullify any tendency of the animal to press harder is determined, at least partially, by the following factors: 1)

Figure 1. Amount of reinforcement as a function of required peak force for four schedules of proportional reinforcement. Curves A and B represent schedules specified in terms of pellets and force-steps procedures which were used by Notterman & Mintz (1965). The straight lines labeled C and D are for the continuously proportional (above 8.0 gm.) reinforcement schedules which are described in the Method section of this chapter.

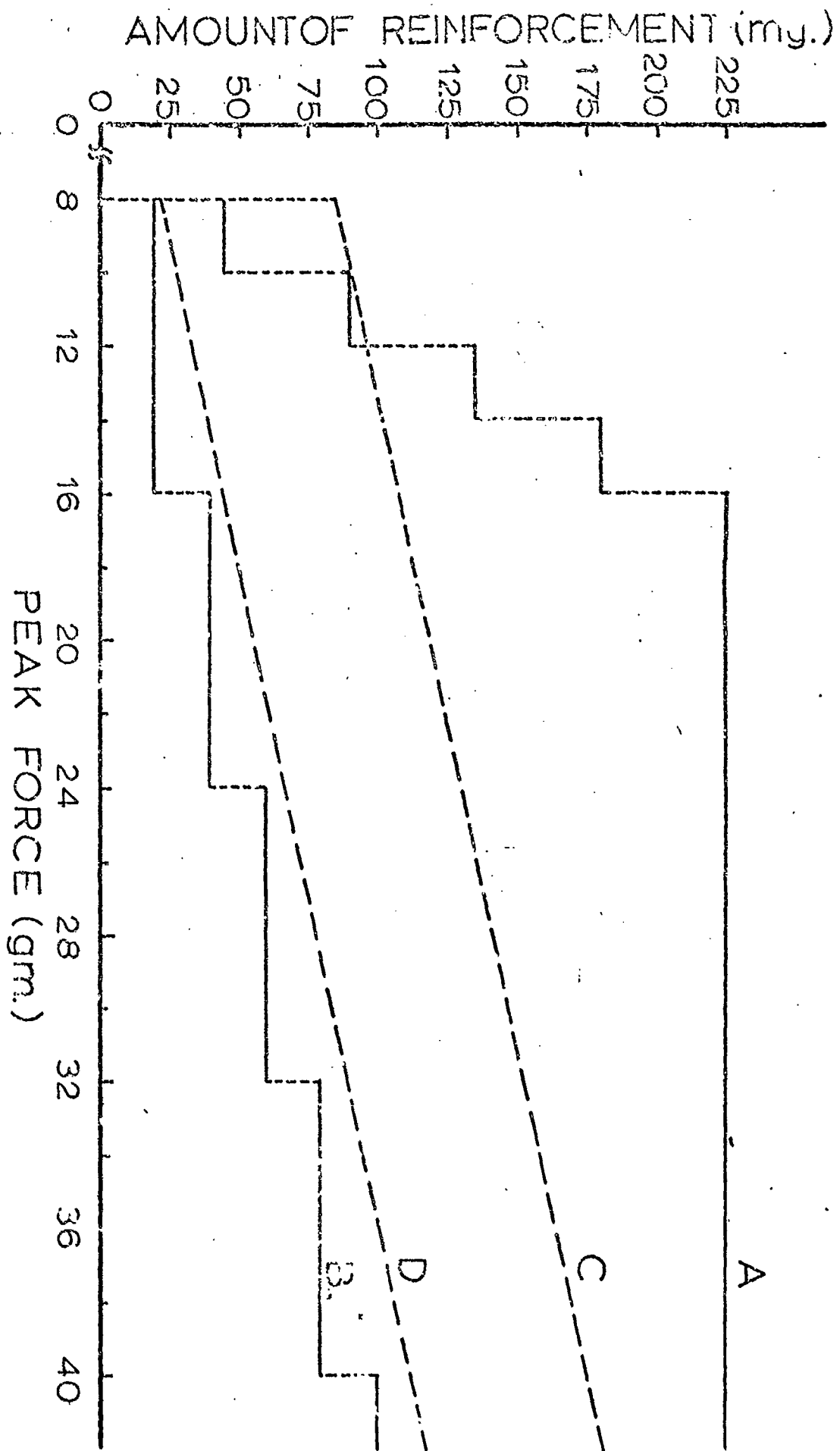
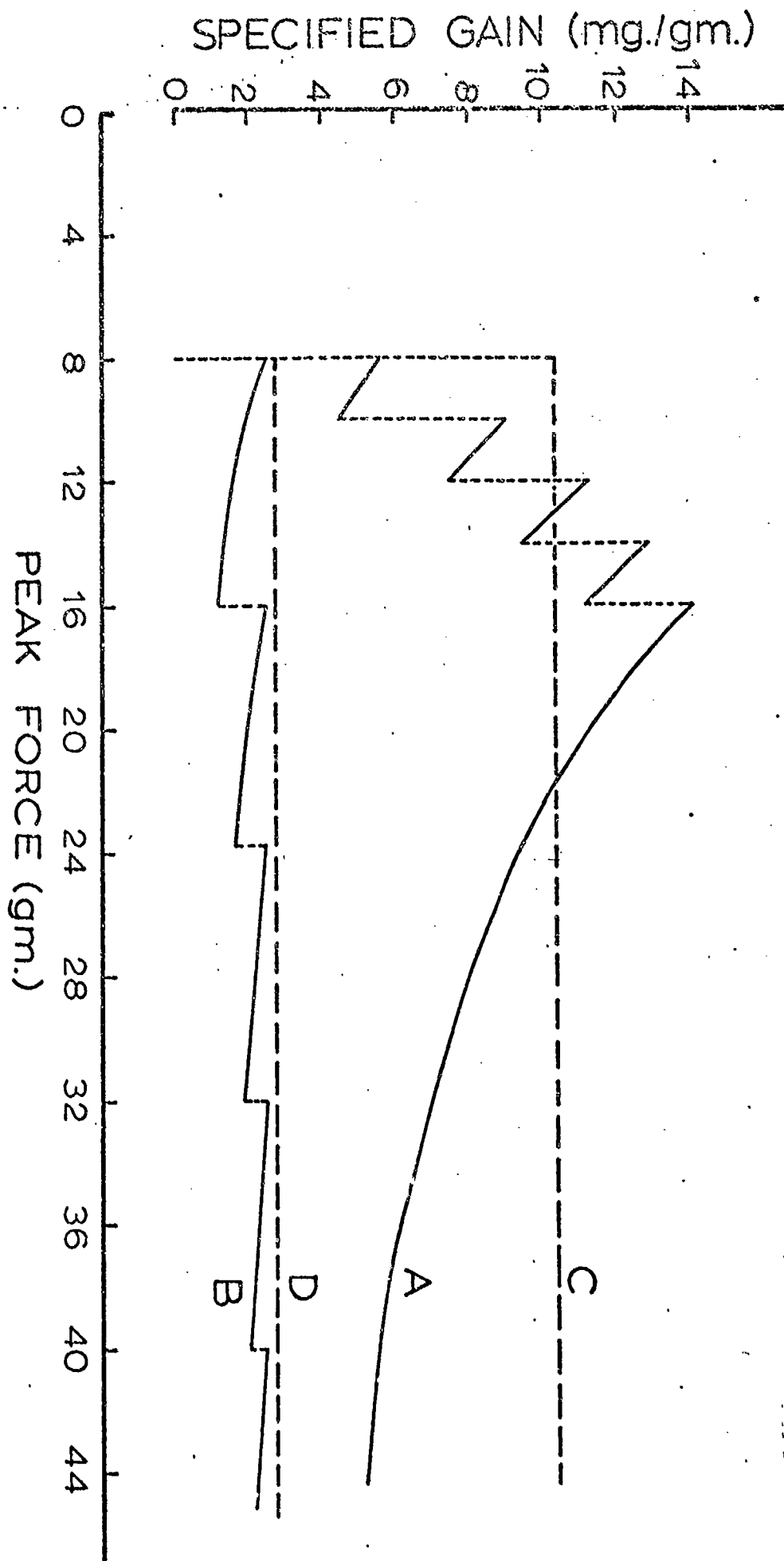


Figure 2. Specified gain as a function of required peak force for the proportional reinforcement schedules given in Fig. 1. The labels on the curves correspond to those in Fig. 1: A and B represent the specified gain of the schedules used by Notterman and Mintz (1965) and C and D depict the specified gain of the schedules used in the present work.



the force discrimination capacities of the organism, 2) the influence of quantity of available reinforcement per response on force level, and 3) the importance of specified gain (or quantity per gram of force) in controlling behavior. Relevant to the first issue are data from the experiments of Notterman & Mintz (1965) which indicate that--for the range of values used here--one cannot rule out the possibility that rats can make the force discriminations necessary for detecting the discontinuities. In turning attention to the second point, one can see from Fig. 1 that the actual reinforcement contingency does not provide more reinforcement per response when the force is above the upper limit. For example, with the "increasing gain" schedule, the application of a 16 gm. response will produce five pellets, but a 24 gm. response will also yield five pellets. Thus, above the upper limit the proportional reinforcement was not really operative, and no cue in terms of quantity of reinforcement per response was provided for the responses over the limit. With regard to the third factor, one should note in Fig. 2 that if the specified gain is important in determining magnitude of response force, then the animal's experiences of obtaining a higher gain value by pressing harder could have been counteracted by the experiences of pressing harder within a given step or above the limit and receiving relatively less per gram of force exerted.

The foregoing comments suggest that evidence for the differ-

ential reinforcement of higher response force might be obtained if the previous apparatus-related discontinuities in gain and quantity of reinforcement could be circumvented. The research described in this chapter sought to accomplish this by employing a technique in which access time to a liquid reinforcer is made directly proportional to force of response by a small analog computer system. This stratagem operationally limits the discontinuity and departure from linearity in quantity of reinforcement 1) to quantization of consummatory activity (licks), 2) to failure to take full advantage of access time, or 3) to the possibility that amount consumed is a nonlinear function of access time. Provisions were made to determine experimentally whether amount of licking and access time are linearly related within the range of times used in the experiment.

Just how a rat discriminates quantity of positive reinforcement has not been explicitly elaborated. Certainly the ability is at least a function of oral and post-ingestional factors. It is also possible (if not highly likely) that "reinforcing effect" and quantity of a particular reinforcing agent are not linearly related. The procedure described above does not attempt to control for this eventuality. However, to assume at least a monotonic relationship, over a limited range, between reinforcing effect and physical quantity of reinforcement seems reasonable.

For the continuously proportional reinforcement schedules

used in the present experiment, the specified gain is held constant for all forces above the criterion (see Fig. 2). Therefore, if the organism does have a proclivity to distribute its forces so as to maximize gain, one would not expect the constant gain schedules to shape forces upward. (An examination of the manner in which variations in specified gain influence response force is presented in Chapter 4.) On the other hand, if reinforcing higher forces with larger quantities of reinforcement does influence behavior, then an increase in force of response should be observed during the course of continuously proportional reinforcement conditioning.

Method

Apparatus

The force recording apparatus used in this study was a modification of the analog computer system described by Notterman & Mintz (1965). In the present case, a Sanborn transducer (Model FTA 100-592) served as the manipulandum. The portion of the transducer available for sensing forces was a 13 mm. diameter disc which protruded above its 27 mm. diameter housing by 1 mm. The disc surface was 62 mm. above the grid floor of a Skinner box and was positioned outside the cage. The manipulandum was essentially isometric, excursion being less than 0.4 mm. for forces up to 200 gm. A Hewlett Packard Digital Recorder (Model 561B) registered peak force (F_p), duration (t), and time integral of force ($\int F dt$) for all

pressures on the disc exceeding 2.5 gm. (termed the "threshold"), which defined a response. Upon termination of pressures above 8.0 gm. ("criterion") the liquid reinforcement magazine was operated.

In order to make reinforcement access time proportional to response force, two chopper-stabilized operational amplifiers (Philbrick Researchers, Model K2-XA) were required in addition to the analog computer system just described. The first of these, the timing amplifier, was connected to the peak force voltage circuit of the computer during a response, and the amplifier output charged a capacitor with the force-equivalent voltage. Immediately at the termination of the response, the timing amplifier was disconnected from the peak force circuit, and the capacitor charge fed back to the input of the timing amplifier along with an adjustable reference voltage. This arrangement resulted in a timing amplifier output which began at a negative value proportional to the force of the response and decayed linearly as a function of time. When this voltage crossed zero and changed to positive sign, a diode passed the output to the second amplifier, which, within .5 sec. of zero-crossing, operated a reset relay, thus ending the time reinforcement period and resetting the entire timing circuit. The reference voltage to the timing amplifier was adjusted so that a one gram increase in peak force above the criterion caused a .5 sec. increase in the interval that the solenoid-operated

dipper (Ralph Gerbrands Co. Model B-LH) remained within reach of S in the Skinner box. Figure 3 presents a calibration curve of the timing portion of the apparatus. The upper limit on the abscissa of this function was 120 gm. The system employed lock-out relays in order to prevent accumulation of additional access time in case (1) S made a criterion response during dipper presentation (these responses were recorded, however) and so that (2) subcriterion responses would not deliver reinforcement.

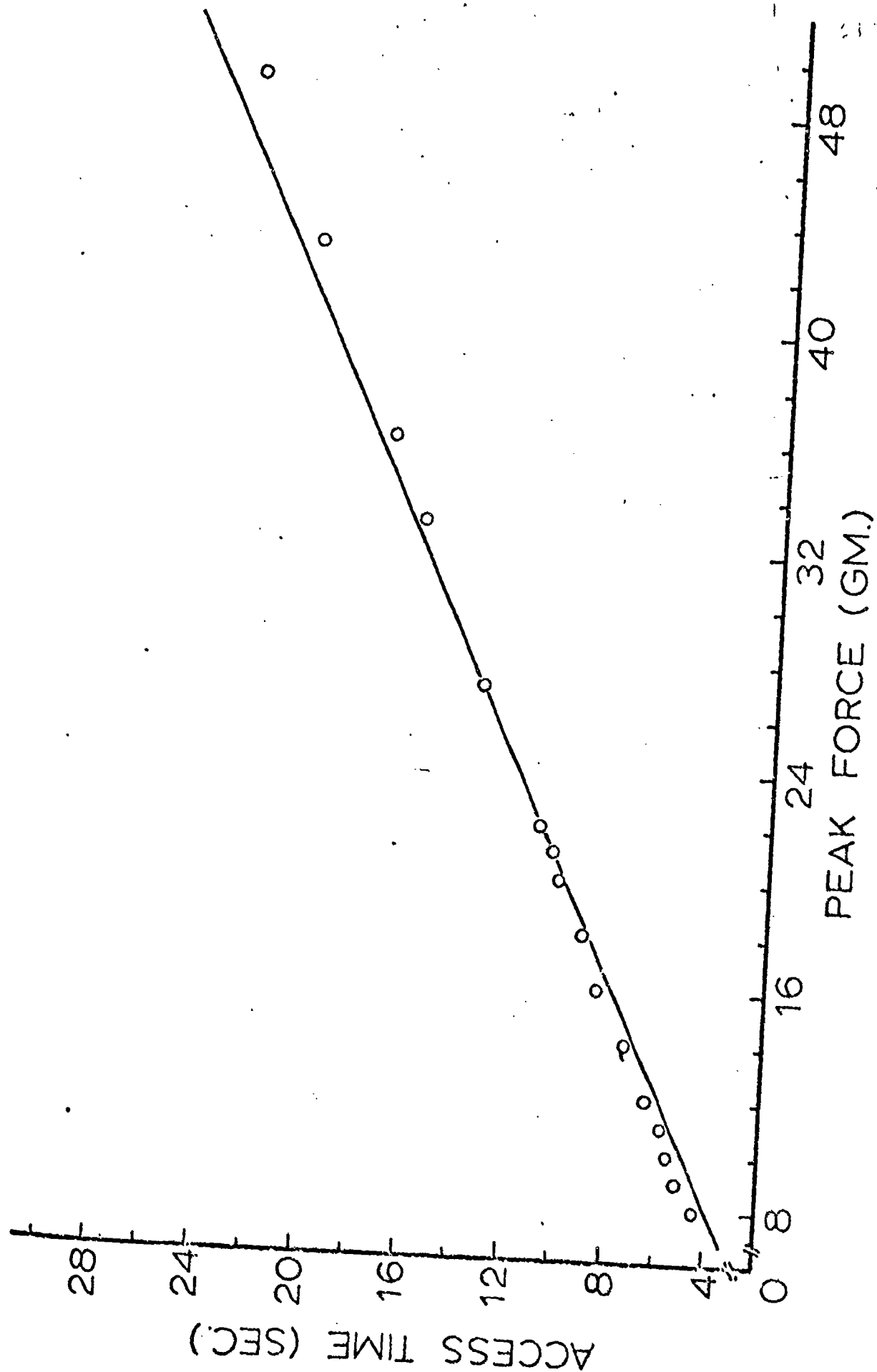
The sensing electrode of a Grason-Stadler drinkometer (Model E4690A) was attached to the dipper arm. The dipper volume (10 ml.) was relatively large, so that the liquid level would change very little even during prolonged reinforcements. Number of licks during each reinforcement were recorded by a High Valley (Model 1530) print-out counter.

The Skinner box was located in a sound insulated room; a white noise generator on the lid of the box provided masking noise. To insure reliable operation of the drinkometer, S was momentarily placed on a mat of wet toweling before transfer to the box.

Subjects and Procedure

The Ss were 21 male Wistar rats with mean weight of 255 gm. at the time of receipt from Camm Research Institute. Ss were housed individually in a room kept on a diurnal cycle; the period of darkness was 11:00 P.M. to 7:00 A.M.

Figure 3. Linearity check of apparatus programming
access time as a function of peak force.



After ten days of ad lib food and water, water deprivation was instituted, and over the course of nine days, time of access to water in the home cage was reduced from 1 1/2 hr. to 1/2 hr. During the latter portion of these nine days, magazine approach training was carried out. Each S received approximately 60 4-sec. reinforcements of water. On the following four days, each S received two 40-reinforcement sessions of shaping. During shaping, Ss were trained to reach out through an opening in the cage wall in order to apply pressure on the manipulandum. This arrangement was designed to increase the likelihood of developing uniform response topography, and to preclude the possibility of biting behavior being recorded as responses.

Following shaping, two days of continuous (i.e., non-proportional, but regular) reinforcement raining were administered (Phase I). Procurement of 30 4-sec. tap water reinforcements terminated a session. During Phase I the number of licks per session and the body weight of each animal were recorded. After the two sessions of Phase I, Ss were switched to a food deprivation schedule (water ad lib) in which 1 hr. access to Purina lab chow was permitted daily; Ss were maintained in this manner for the remainder of the experiment. The daily ration was given 1/2-1 hr. after S completed a session. Four days of accommodation to the food deprivation schedule were allowed before the onset of Phase II¹. In general, Phase II

¹ No more time for adjustment to food deprivation was provided because only data from the last of 20 daily sessions was used in the analysis. Thus the data analyzed were based on 24 days of adjustment.

involved sucrose solution as reinforcement; hence, the prior steps of adjustment to both water and food deprivation. (See Guttman, 1953).

The 18 Ss (by this time three had died) were randomly divided into three groups of six each, which were matched for peak force, body weight and lick rate in Phase I. During the 20 sessions of Phase II, a continuous reinforcement group (C8) received 4-sec. access to an 8% sucrose solution for each criterion response. Two proportional reinforcement groups received 8% sucrose (P8) and 32% sucrose (P32), respectively. For both P8 and P32, the amount of access time (sec.) earned was one-half the magnitude of the force (gm.) exerted for responses exceeding criterion. In terms of access time the gain was 0.5 sec./gram. The specified gain (in terms of mg./gram) of these proportional reinforcement schedules could only be estimated from Ss lick volume and lick rate. Stellar & Hill (1952) report that there are but small individual differences in lick rates in rats, an average value being 6-7 licks/sec. Since these Ss would be consuming solutions more viscous than water, measurements were taken on the 7th day of Phase II in order to determine the lick rate and lick volume for the present experimental conditions. (Amount of reinforcement and specified gain are plotted as a function of required peak force in Fig. 1 and Fig. 2, respectively. The curves labeled C are for Group P32, and the curves designated D are for Group P8.) Throughout Phase II, a session was terminated after 750 licks had been obtained. S was allowed to finish the last reinforcement period even if the session ended during that reinforcement. Subject #33 died on the 8th day

of Phase II, reducing the number in P8 to 5.

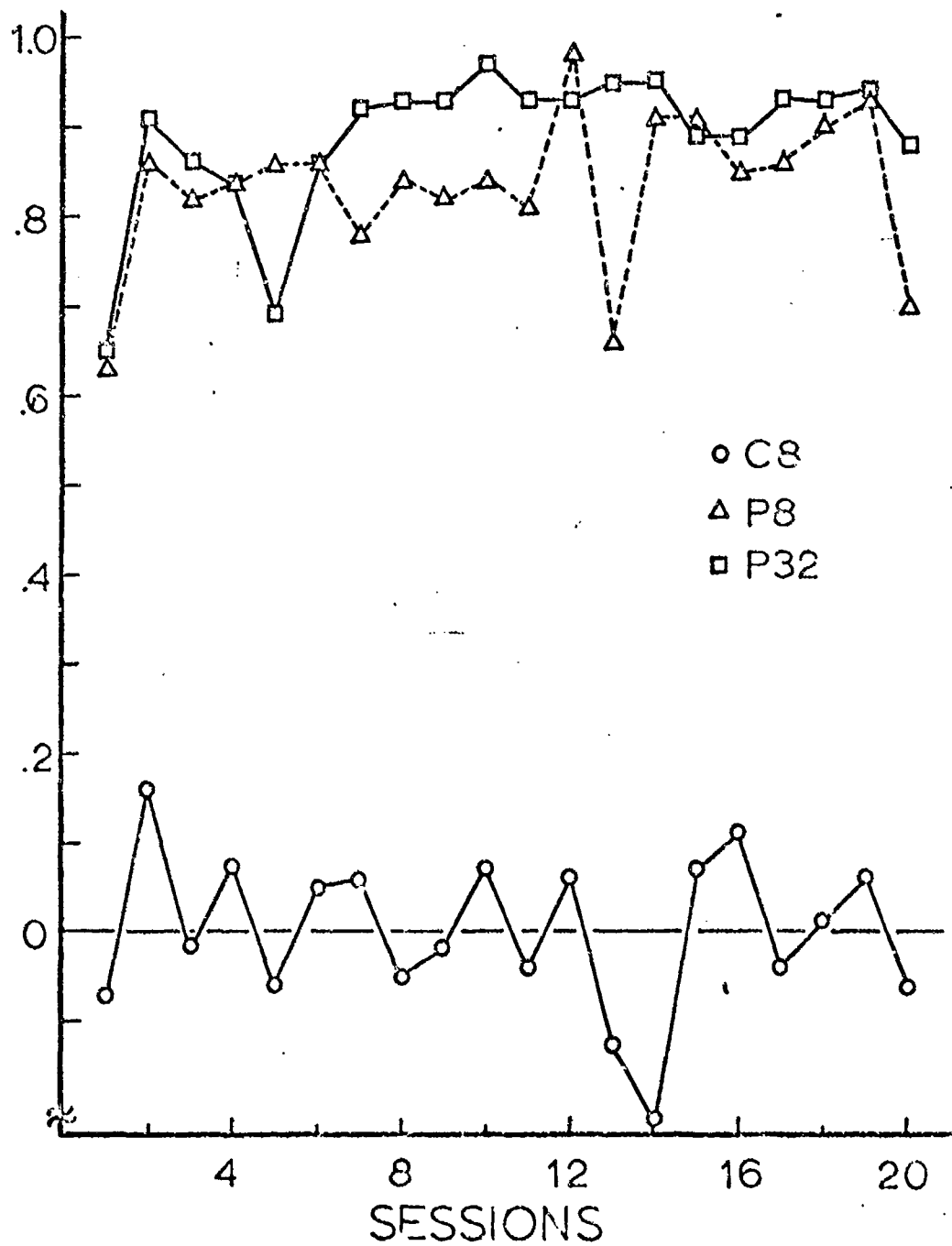
Sucrose solutions were prepared on alternate days from commercial granulated sugar and tap water. The solutions were always mixed several hours before use to allow them to reach room temperature. The percent specification is weight percent of solute; i.e., the 8% solution was .371M and the 32% solution was 1.484M.

Results and Discussion

Measurements taken on the 7th day of Phase II revealed that Group P8 was licking at the rate of 4.7 licks/sec. on the average and that Group P32 had a rate of 3.7 licks/sec. Probably because of differences in viscosity, both values are lower than the 6-7 licks/sec. that Stellar & Hill (1952) reported. Appropriate calculations indicated that the specified gain for Group P8 was 2.8 mg. sucrose/gm. of response force (curve D in Fig. 2) and for Group P32, 10.4 mg. sucrose/gm. (curve C in Fig. 2). Figure 4 shows the average correlation of forces above criterion with the number of licks for the associated reinforcement. Each point is the group average for a given day. Average correlation coefficients for Phase II for individual animals in the proportional reinforcement groups ranged from a low of .807 to a high of .940. The data, therefore, indicate that Ss were in fact being reinforced with an amount approximately proportional to their forces. Moreover, it is reasonable to assume that this proportionality was

Figure 4. Group mean correlation coefficients of supra-criterion peak force and number of licks as a function of training.

MEAN CORRELATION OF CRITERION
FORCE AND NUMBER OF LICKS



virtually continuous since response force and access time were continuously related electrically. Figure 5 is a typical session record showing the consummatory behavior during the proportional reinforcement intervals.

Having established that a continuously proportional reinforcement schedule was operative for Groups P8 and P32, attention may now be directed to the main research question: How do the proportional contingencies affect response force?

Table 2 summarizes the principal results of the experiment: Neither of the proportionally reinforced groups is substantially higher in mean peak force than the control group. Proportional reinforcement defined in terms of access time does not bring about significantly more vigorous bar-pressing. Either the organisms were not making the necessary discriminations in quantity of reinforcement, or there is no particular advantage to their doing so.

The first of these alternatives can be only partially answered by examining the possibility that changes in quantity of reinforcement, occasioned by variations in response force, were insufficient to allow the organism to detect them. Figure 5 is the reinforcement record for a typical S in group P32 for session 20 of Phase II. The "spikes" are cumulative records of licking during the single reinforcement periods which are represented by a downward deflection of the event pen. The average relative change in access time, and thus quantity (mg.)

Figure 5. Cumulative records of number of licks during each reinforcement interval of session 20 of Phase II. The period of time elapsing between a and b is the inter-reinforcement interval. The interval between b and c is the time that the reinforcement dipper was within reach of the rat's tongue.

#37 GROUP P32

60 LICKS
40 SEC.

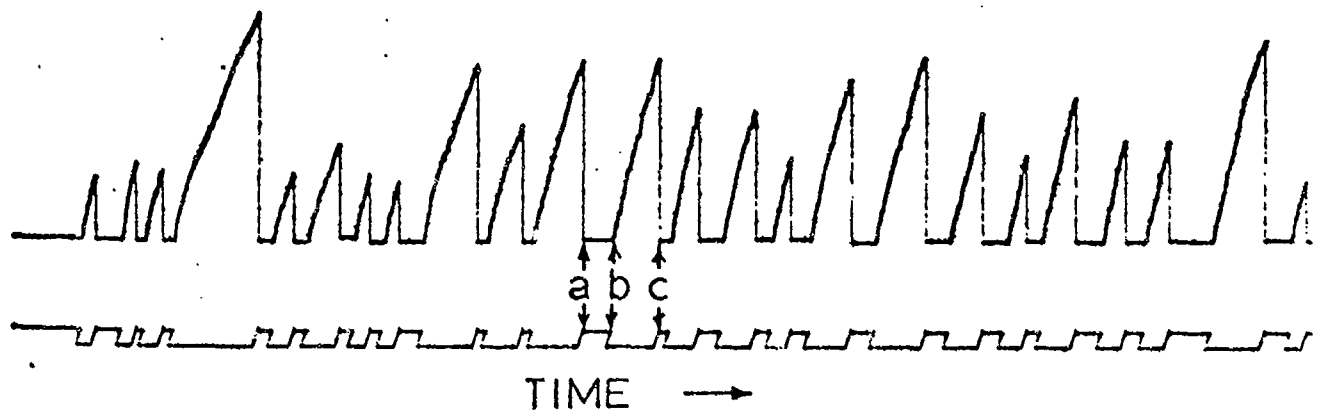


Table 2

Group Means of Selected Variables
for Session 20 of Phase II

Variable	Group C8	Group P8	Group P32	Assessment of Confi- dence Level Based on Kruskal-Wallace Test
mean peak force (gm.)	11.8	12.7	12.7	$p > .10$
standard devi- ation of peak force (gm.)	5.03	5.57	6.59	$p > .10$
rate of ₁ res- ponding (R's/min.)	9.1	6.2	5.9	$p < .05$
interresponse time with drinking time removed (sec.)	3.0	2.5	2.7	$p > .10$
reinforcement rate ₂ (mg. of sucrose/min.)	136	166	647	$p < .01$

- Notes: 1. Both P8 and P32 taken separately are significantly lower than C8, $p < .05$; but P8 and P32 do not differ from each other $p > .10$. (These comparisons and the ones below are based on Wilcoxon's Rank Sum Test.)
2. P32 is higher than either P8 or C8, $p < .05$; however, the difference between P8 and C8 only approaches significance, $.05 < p < .10$.

of reinforcement, can be computed from these data. During the course of this session, there were 25 criterion and above responses; and, in going from one reinforcement to the next, there are 24 possible changes in access time. The mean value of these changes is 0.71, and 14 of them are greater than 0.35, the value that Tarpy (1967) obtained for the Weber fraction for time discrimination in rats. Thus if consummatory time provides a sufficient cue for discriminating quantity of reinforcement, many opportunities were available for the rats to experience these differences. Moreover, in terms of milligrams of sucrose many of the changes in quantity are similar in magnitude to shifts in amount (mg. of dry pellets) of reinforcement which have been observed to influence response force (Notterman & Hintz, 1965, Chapter 10). Despite the evidence that cues for detecting variations in quantity of reinforcement were available, it is still possible that the close temporal proximity of the various changes in quantity precluded their detection because of the rat's inability to form or maintain a consistent "standard" with which subsequent quantities could be compared. Of course, other cues such as caloric value, taste, stomach distention, tonicity, etc., are also important to the organism in detecting changes in quantity of reinforcement; however, the present data do not permit an assessment of the relative roles of these various possible cues, although taste factors in particular are examined in a subsequent experiment (Chapter 3).

The second possibility of there being no particular advantage in terms of efficiency in pressing harder per response may be related to the option available to the rat of pressing again rather than harder. Further, as previous research has demonstrated (Filion, Fowler, & Notterman, 1969) reinforcement rate may reflect the degree to which each strategy is chosen. Moreover, several experiments have shown that hungry animals tend to meet the contingency of complex reinforcement schedules by maximizing reinforcement rate (Herrnstein, 1961; Neuringer, 1967). From Table 2 it can be seen that the reinforcement rate for both of the proportionally reinforced groups is higher than that of the control group. This observation is in contrast to the lower overall rate of responding for these two groups (P8 and P32). The joint occurrence of low response rate and high reinforcement rate for the proportionally-reinforced groups is accounted for primarily by the fact that these animals spent relatively more time drinking than the controls. For example, the emission of a 15 gm. response by S in Group P8 would delay the next response for 7.5 sec. (it has already been shown that Ss largely took advantage of access time); on the other hand, a 15 gm. response made by S in Group C8 would delay the next response only 4.0 sec. The comparable magnitudes of the inter-response times (independent of consummatory time) for the three groups suggest that ^{the proportionally} reinforced groups were bar-pressing as fast as was consistent with continuous consumption of each

reinforcement. These two groups (P8 and P32) obtained more reinforcement/min. because of the variability in response force and because of the gain of the schedule, not because the ss were working "faster" or "harder." This follows from the fact that there were no reliable intergroup differences in standard deviation of peak force (see Table 2). Therefore, the rate and force of responding displayed by Group C8 would have produced reinforcement rates similar to Group P8 or Group P32 if the control group had been exposed to the proportional schedules. Thus the data suggest that the option of pressing more often is manifested to about the same degree by the three groups. Perhaps if an additional premium were placed on pressing harder, then this alternative strategy would be selected. For example, one could construct a proportional reinforcement schedule so that higher concentrations of sucrose could be obtained by pressing harder but not by responding faster (see Chapter 3).

While the results of this experiment indicate that a force proportional reinforcement contingency defined in terms of volume drunk (number of licks) or milligrams consumed does not increase the probability of higher forces being emitted, they do direct attention to the importance of the animal's ability to discriminate quantity of reinforcement and its proclivity to press again rather than more forcefully. A second experiment, which is the subject of the next chapter, attempts to demon-

strate the selective reinforcement of high response force by making concentration of sucrose proportional to force of response, a tactic which provides a greater opportunity for discrimination of quantity of reinforcement and thereby may increase the likelihood of pressing harder rather than more often.

Chapter 3

Force-Proportional Concentration of Sucrose Reward

Listed in Chapter 1 were five variables which taken singly or collectively probably acted to prevent successful demonstration of control of response force by proportional reinforcement. In view of the results described in Chapter 2 the fifth variable--apparatus limitations as they contributed to the discontinuous nature of the contingencies--may be safely eliminated. The four remaining variables are examined experimentally in this and the subsequent chapter.

By his specification of proportional reinforcement contingency in terms of concentration of sucrose solution, and by his particular choice of the absolute quantities (mg.) of sucrose involved, the investigator has sought to design the present experiment so as to encompass three of these variables: 1) the absolute quantity (mg.) of reinforcement obtained per response as it influences force of response, 2) the choice available of pressing again rather than harder; and 3) the capacity of the organism to discriminate changes in quantity of reinforcement and changes in motor feedback cues. The role of specified gain, the fourth variable, is examined in Chapter 4. Summarized in Table 3 are the reinforcement parameters of the present experiment.

Previous research has demonstrated a relationship between

Table 3

Summary of Experimental Groups and Associated Reinforcement Contingencies

Group	Force Require- ment (gm.)	Concentration of Sucrose (%)	Concentration Gain ¹ (%/gm.)	Sucrose Amount (mg.)	Amount Gain (mg./gm.)	Solution Volume (ml.)
1 (N=7) (Regular reinforcement)	8.0 +	8.0	1.0	6.35	.79	.05
2 (N=8) (2-step prop. concentration)	8.0-23.9 24.0 +	8.0 24.0	1.0 1.0	6.35 19.05	.79 .79	.05 .05
3 (N=8) (5-step prop. concentration)	8.0-11.9 12.0-15.9 16.0-19.9 20.0-23.9 24.0 +	8.0 12.0 16.0 20.0 24.0	1.0 1.0 1.0 1.0 1.0	6.35 9.53 12.70 15.88 19.05	.79 .79 .79 .79 .79	.05 .05 .05 .05 .05
4 (N=7) (5-step prop. volume)	8.0-11.9 12.0-15.9 16.0-19.9 20.0-23.9 24.0 +	8.0 8.0 8.0 8.0 8.0	1.0 .67 .50 .40 .33	6.35 9.53 12.70 15.88 19.05	.79 .79 .79 .79 .79	.050 .075 .100 .125 .150

¹The gain values were computed following Notterman & Mintz (1965), who suggested dividing the reinforcement quantity by the lower force requirement for that quantity.

mean peak force and amount (mg.) of reinforcement per response (DiLollo, Ensminger, & Notterman, 1965; Notterman & Mintz, 1965). These results considered along with those just reported suggest that amount of reinforcement per response and mean peak force can be expected to covary within a limited range. This generalization poses difficulties, however, for predicting the outcome of proportional reinforcement operations. Specifically, for a given peak force distribution, a proportional reinforcement contingency makes available much more reinforcement per response than its non-proportional counterpart - regular (or continuous) reinforcement. Thus, although one might intuitively expect proportional reinforcement to select high forces, at the same time one might anticipate that the amount of reinforcement obtained per response would thereby increase, perhaps reciprocally tending to decrease mean peak force. Furthermore, if sweetness as well as amount is made proportional to peak force, then the force decreasing effects of greater amounts might be enhanced, because not only would the amount increase but also the taste stimulation. Thus proportional reinforcement procedures using positive reinforcers may be inherently self-defeating. For these reasons the importance of the values and range used for amount of reinforcement per response becomes crucial.

The critical role of amount (mg.) per response is manifested in at least two ways. First, suppose two groups of rats are exposed to the same proportional reinforcement contin-

gency in terms of amount (mg.) available per response (Groups 3 and 4 in Table 3). Further, suppose that Group 3 receives taste cues correlated with the peak force requirements. Under these conditions one can presume higher peak forces on the part of Group 3 as evidence that these subjects pressed harder to obtain the sweeter solutions. On the other hand, should Group 3 prove to be lower than or equal to Group 4, one could conclude that the taste stimulation has little additional effect on peak force. This latter outcome would also suggest that proportional reinforcement acts only to increase the amount of reinforcement per response which in turn reduces mean peak force. Comparison of mean F_p for these groups should provide some decision on this issue. If, in a proportional reinforcement situation, the amount obtained per response really represents an equilibrium point between the tendency to press harder to get more versus the opposing tendency for amount obtained per response to decrease force, then mean peak force and amount obtained per response should be highly correlated. Therefore, for any two groups sharing a common lower criterion and receiving similar amounts (mg.) per response (as a consequence of their behavior), the force levels should be similar. However, should one of the two groups receive a force-correlated taste cue, and should this group display the higher peak force, then such a finding would be evidence of the efficacy of taste proportionality in establishing control of peak force. For example, Group 2 shares

lower limit criterion of 8.0 gm. with Group 4. But for a given distribution of emitted peak force, more reinforcement is available for Group 4 than for Group 2. Therefore, if Group 2 comes to settle for a level of amount of reinforcement per response roughly equivalent to that of Group 4, then such behavior can be interpreted as demonstrating the existence of the tendency for rats to press harder to get sweeter reinforcements.

From a parametric point of view the absolute quantity of reinforcement available per response may have important implications for proportional reinforcement experiments. That is, the use of either greater or smaller quantities than those previously tried might have produced evidence for the selective shaping of high response force. In previous studies, the smallest amount (mg.) as well as ^{the} smallest increment in reinforcement was a 20 mg. food pellet. In Chapter 2 of this paper, 22 mg. (dry weight of sucrose actually in solution) was the smallest amount used. These quantities may have been so large as to render any tendency to press harder essentially unimportant compared to the tendencies to conserve energy and to maintain a satisfactory reinforcement rate. Inspection of Table 3 reveals that 6.35 mg. of sucrose is the smallest amount available per response in the present experiment. Group 1 and Group 4 serve as anchor points for assessing the degree to which proportional reinforcement may control peak force independently of taste when very small amounts are used. Using such small

quantities has the advantage of reducing possible effects of satiation, which may be the underlying basis of the previously observed relationship between mean peak force and amount of reinforcement (cf. DiLollo, Ensminger, & Notterman, 1965).

Defining proportional reinforcement in terms of concentration of sucrose should place a premium on pressing harder--rather than more often--and thus should provide some degree of control over any proclivity to favor rate over force. This follows from the fact that the sweeter solutions can be obtained only by relatively greater force - rate of response alone cannot contribute to the procurement of the sweeter reinforcements. Nevertheless, rate of response can still affect the overall rate at which reinforcement is obtained. For these reasons the present experiment should provide more information on the way force and rate interact to influence reinforcement rate.

Consideration of the discriminative capacities of the organism encourages the specification of proportional reinforcement schedules in a discontinuous manner - a procedure criticized in Chapter 2. In fact, inherent in the 2-step contingency for Group 2 (see Table 3) is a degree of discontinuity which far exceeds that found in the earlier proportional reinforcement experiments (Notterman & Mintz, 1965; Fillion, Fowler, & Notterman, 1969), though it is consonant with techniques used by Hendry (1962). Despite the previous criticisms, two considerations recommend this procedure. First, the results reported in Chapter 2 imply that the discontinuities were not import

in preventing the upward shaping of response force in previous research, because removal of the discontinuities had virtually no effect on peak force. Second, the discontinuities in amount of reinforcement and in the correlated force requirement may actually be essential to the organism's discrimination of changes in quantity of reinforcement and changes in motor feedback cues. Thus, the proportional reinforcement studies cited above did not obtain positive results perhaps because the operations did not include sufficiently distinguishable steps. The concentrations of sucrose and the force requirements for Group 2 were selected with a view toward assuring that the two values on each continuum would be easily discriminable from one another. The Weber ratio for sucrose solutions in hungry rats is probably between .25 and .50 for the range of values used in this experiment (Campbell, 1958). Also 24% is near the value which produced the maximum rate of response in Guttman's (1954) study. Therefore, rats exposed to the Group 2 contingency should easily discriminate the changes in quantity of reinforcement since a 200% change is involved. No clear-cut psychophysical data on force discrimination in rats are available; therefore, the choices of the force requirements were somewhat arbitrary, though they were selected so as to be comparable to values used fruitfully in previous research efforts.

In choosing the force requirements, it is important to consider whether the rats themselves emit a sufficiently broad

range of forces during the initial sessions of training as to assure that all the force-reinforcement contingencies of a proportional schedule are sampled. To increase the likelihood of this happening, the bar-press response was reinforced during a preliminary phase without regard to actual force emitted.

Reinforcement delivery was based only on response topography; i.e., paw-pressing. If it is assumed that this procedure initially reinforces a sufficiently broad range of forces, it must also be assumed that the "random" shaping might produce initial mean F_p values which differ widely from one another. This latter observation has two important implications for evaluating the mean F_p data. First, the changes which individual animals display during the course of conditioning should be interpreted in the light of both their initial F_p distributions and the particular force requirement to which they were exposed. For example, in order to provide evidence of responsiveness to proportional reinforcement, an animal in Group 2 with an initially high mean F_p need not display an increase in mean F_p . It is sufficient for the animal to maintain its high level of response force. On the other hand, an animal in Group 2 which begins at a low mean F_p , but remains there, is probably not responding to the force-correlated sweetness of the schedule. A second implication of the shaping procedure is that statistical comparisons between the independent groups should be made only after extended conditioning, when the influence of the preliminary shaping has become minimal.

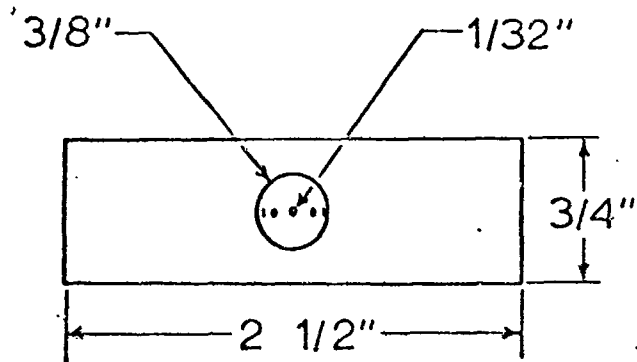
In view of the foregoing rationale the present experiment is seen as addressing itself to these specific questions: 1) When sweetness of reward is correlated with force requirement do rats press harder to obtain the sweeter solutions? 2) Independently of taste factors, do proportional reinforcement schedules based on very small quantities of reinforcement lead to the emission of high force? (That is, were previous failures to demonstrate the supposed effect merely the result of an unfortunate choice of parameters?) 3) How do force and rate of response interact in determining the overall rate of reinforcement?

Method

Apparatus

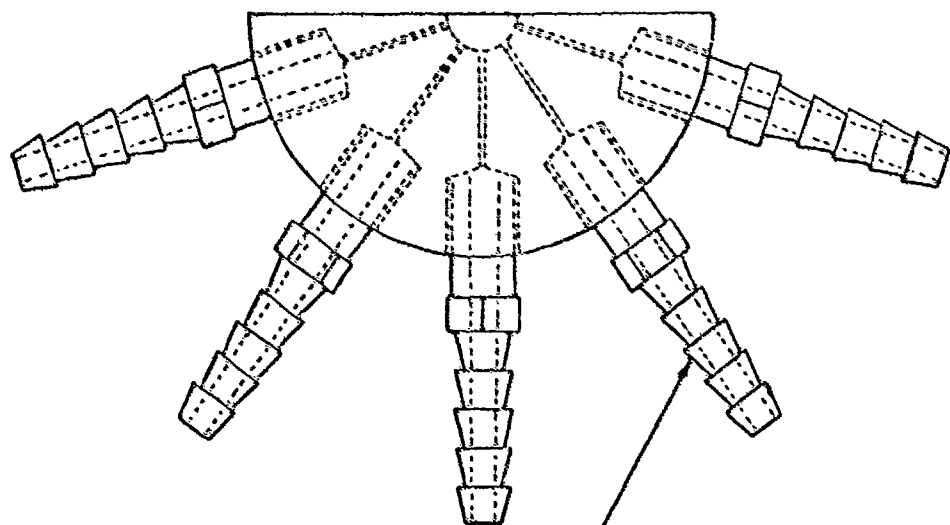
The response measuring and recording equipment was identical to the apparatus described in Chapter 2. However, the delivery of sucrose solutions was carried out in an entirely different manner. Five liquid solenoid valves (Lehigh Valley Electronics, Model 1527) were individually connected by means of 1/4" tygon plastic tubing to a special food cup made of machined brass (see Fig. 6). Each of the five reservoirs connected to the valves contained a different concentration of sucrose solution. Calibration of each of the valves was accomplished by manual adjustment of the flow-rate needle valve and by fine adjustments of the pulse width which operated the solenoid valve. Since the contingencies for Group 4 involved only one concentration, the volume of liquid dispensed by the 8% valve

Figure 6. Sketch of reinforcement cup, drawn to actual size.



TOP VIEW

SIDE VIEW



HOSE NIPPLE

after each effective response was controlled by five interval timers. Various electrical gates, pulse formers, relays, etc. were used to select the appropriate timer corresponding to the magnitude of force exerted on the manipulandum.

Inasmuch as the solenoid valves operated with a minimum of noise, a pellet dispenser was wired to produce a single click each time a supra-criterion response was terminated. Because of the large number of "and" gates and relays used in programming the reinforcement, there was an interval of about .6 sec. after termination of such responses during which the reinforcement equipment was unresponsive to subsequent responses. Further, measurement and recording of pressures on the manipulandum did not occur during the first .25 to .30 sec. of this interval.

Subjects and Procedure

The subjects were 32 male Sprague-Dawley rats supplied by Charles River Breeding Laboratories. The animals were housed individually. Five days after receipt, the animals were placed on a 23-hr. hunger rhythm which provided 1-hr. access to Purina lab chow once per day. Water was continuously available in the home cage. Twenty-three days of this regime preceded initiation of the experiment at which time the mean body weight was 311 gm. A daily period of darkness from 11:00 P.M. to 7:00 A.M. was provided in the vivarium.

Magazine training and shaping (Phase I) were carried out in the manner described in Chapter 2, except reinforcements

always consisted of .05 ml. of 8% sucrose solution during this phase. During shaping, reinforcement was delivered only on the basis of response topography; the force of response was not taken into account. This procedure was used to insure that Ss would emit a broad range of peak forces during the initial session (s) of acquisition, thereby increasing the likelihood that all the force requirements and their associated reinforcements would be sampled. Two subjects were discarded during Phase I because of their extremely aberrant response topographies. The remaining 30 subjects were randomly assigned to the four groups listed in Table 3. Acquisition (Phase II) began immediately after Phase I and continued for 15 daily sessions. Each session was terminated after procurement of 50 reinforcements regardless of the number of reinforcements obtained at each force level. Subjects were run in a counter-balanced order so that one subject from Group 3 was followed by a subject from Group 2 which in turn was followed by a member of Group 1, and so on. The same order was maintained throughout Phase II. During Phase II the subjects were maintained on a 22-hr. hunger rhythm which provided one hour access to mash approximately one hour after a session.

Sucrose solutions were prepared from tap water and commercial sugar every three or four days. The entire reinforcement dispensing apparatus, including tubing and valves, was washed thoroughly before the fresh solutions were placed in the reservoirs, and the solenoid valves were recalibrated.

Results and Discussion

Since evidence that sweetness of proportional reinforcement influences response force may be available from the performance of individual animals, as well as from intergroup comparisons of mean F_p and other variables, the analysis which follows examines both sources of information.

Table 4 presents the mean and standard deviation of F_p for each of the subjects for the first and last three sessions of Phase II. The last three sessions were combined because mean peak force had ceased to change over these sessions. Choosing the last three sessions as being representative of stable performance suggested the further choice of the first three sessions so as to provide a comparable number of observations in the initial and final distributions. Table 4 also gives the results of t tests of the differences in the initial and final means (see note 1, Table 4). It is clear that there are substantial individual differences in the way the subjects change during the course of Phase I conditioning. However, within each of the groups there appears to be some consistency in that the changes in the mean generally reflect the force requirements imposed, except possibly for Group 4. For example, in Group 1, five subjects display a significant change - four are decreases and one an increase. The one subject which increases was the lowest in the group during the initial sessions. Thus, the increase for this animal may merely be a reflection of the

Table 4

Some Parameters of the Individual Animal Force Distributions
for the Initial and Final Sessions of Phase II

Group	Subject	Initial			Final			t
		Mean	S.D.	N	Mean	S.D.	N	
1	3	22.4	18.1	227	14.1	7.8	191	-6.199****
	9	13.9	11.6	226	12.8	6.8	202	-1.254
	16	21.2	12.7	191	14.0	7.4	184	-6.739****
	17	30.0	20.1	186	21.9	10.0	167	-4.809***
	21	26.0	18.0	209	19.8	13.6	196	-3.908***
	29	11.4	7.5	258	13.6	9.7	205	2.667**
	35	13.7	6.4	180	14.2	7.8	194	0.625
	Mean	19.8			15.8			
2	5	22.0	16.0	193	19.3	14.3	198	-1.728
	11	14.6	11.0	229	32.5	16.8	166	11.978****
	13	17.7	9.4	186	16.3	7.4	181	-1.569
	14	15.8	13.6	236	28.2	32.2	233	5.406***
	15	20.1	13.6	205	24.0	20.8	225	2.311*
	23	26.1	22.3	189	30.3	23.6	155	1.706
	30	23.1	19.9	201	27.7	33.5	237	1.795
	Mean	18.8			23.7			
3	1	12.4	10.7	292	27.3	20.0	185	9.355****
	2	19.5	14.4	201	18.4	14.7	211	-0.737
	6	27.0	19.0	185	25.3	14.5	234	-1.016
	8	12.6	8.1	218	8.3	3.5	269	-7.258****
	20	15.2	10.9	207	20.2	13.3	194	4.128***
	28	11.1	9.2	289	17.2	7.8	176	7.743****
	36	13.3	8.1	203	19.1	8.5	161	6.530****
	Mean	15.4			19.9			
4	4	15.4	11.0	249	19.9	19.3	225	3.089**
	10	15.8	8.6	186	11.1	4.9	199	-6.450****
	18	11.6	11.1	290	12.9	11.0	304	1.408
	25	16.7	10.7	209	19.8	14.4	244	2.597**
	26	11.4	9.3	282	20.4	19.5	234	6.441****
	31	15.0	9.2	202	14.5	12.0	230	-0.479
	34	15.3	10.6	224	13.4	10.3	266	-1.932
	Mean	14.4			16.0			

Notes:

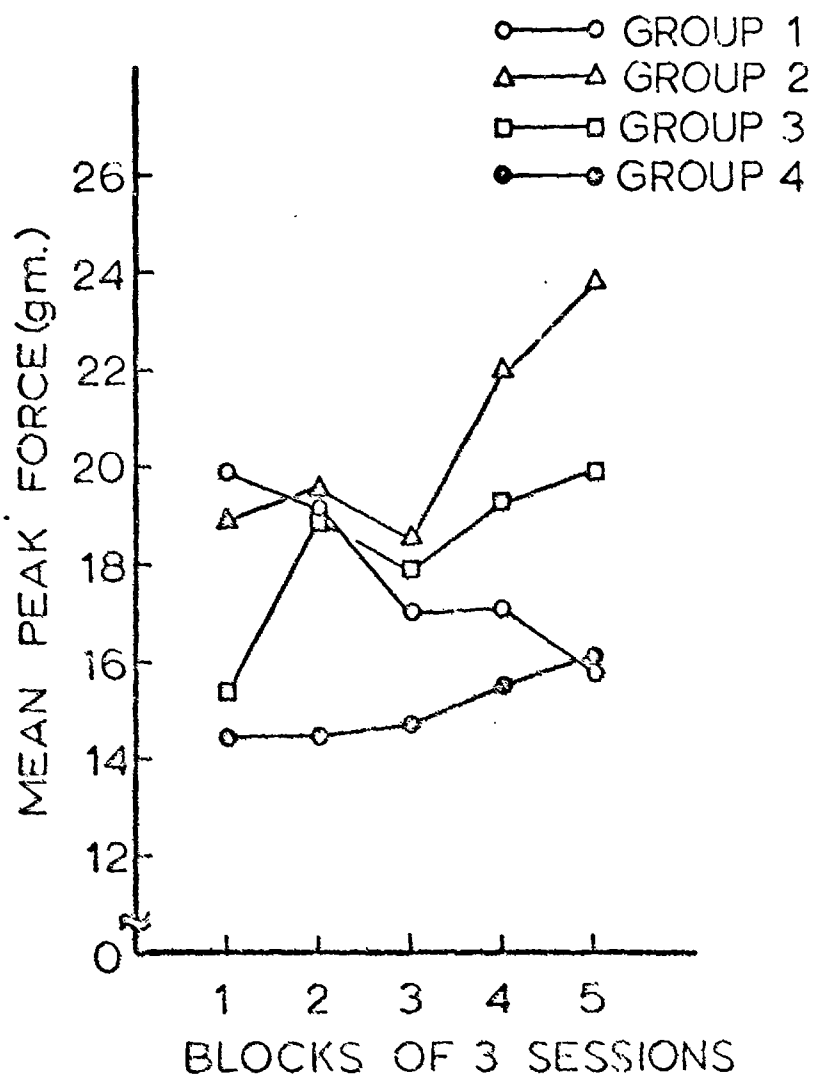
1. The individual animal distributions are clearly non-normal, obviously, they are not homoscedastic. The distributions are, however, unimodal. The t tests were based on the raw data. As shown in Chapter 5 a log₁₀ transformation does bring these distributions closer to normal. Nevertheless, statistical tests based on the log₁₀ transformed data do not substantially alter the outcome. Thus, the raw data were used here to give the reader a firmer feel for the actual quantities involved.

2. "-" means a decrease during training; *p < .05, **p < .01, ***p < .0002, ****p < .000001.

initial sub-normal level of responding. The general tendency for Group 1 to decline in mean \bar{F}_p as a function of training (see fig. 7) is consistent with the findings of Notterman & Mintz (1965), although the rate of change is much slower in the present case. The significant changes in \bar{F}_p for the subjects in Groups 2 and 3, in all cases but one (#8), are compatible with the expectations outlined earlier. If the force proportional sweetness did act to condition the emission of high response force, then subjects in Groups 2 and 3 should show increases in \bar{F}_p during conditioning or they should display no significant change. The single exception, #8, which decreases significantly in mean \bar{F}_p , invites a variety of conjectures: It may be an indication that this subject was deficient in gustatory sensitivity. Or, equally plausible is the possibility that some rats find it advantageous to press harder to get sweeter tastes and others do not. For Group 4, the changes in \bar{F}_p do not present as clear a picture as the other groups. Whereas the performance of #26 may suggest an adventitious rise in peak force because of the subject's initially sub-normal level, the increases of #4 and #25 perhaps indicate a real tendency to press harder to get more of the same solution. This possibility is examined more closely in the following analysis. (The possible effects of specified gain are reserved for consideration in Chapter 4.)

Examination of the individual subjects' data does not afford firm decisions on the questions raised earlier. For

Figure 7. Mean F_p as a function of Phase II training for the four experimental groups. Each data point is the group mean of individual subject means for a block of three sessions.



this reason, a one-way analysis of variance using the method of planned comparison (Hays, 1963, pp. 460-471) was conducted on several variables for the final sessions of Phase II. Table 5 summarizes the questions and their probable answers. The computations were made with and without subject #8 in order to see how inclusion or exclusion of this possibly aberrant subject influences the confidence of the decision. (Subject #8 was included in the plots of the group data which are presented in Figs. 7, 8, 9, and 10 for mean F_p , amount of reinforcement/response, reinforcement rate, and rate of response respectively.) The statistical evaluation of mean peak force does suggest that, on the average, rats will emit higher forces to obtain sweeter tasting solutions (affirmative answers to 2, 4, and 5). This conclusion is buttressed by the results obtained for amount (mg.) of reinforcement/response. It is clear from Table 5 and Fig. 8 that Group 3 displays an increasingly (by sessions) higher amount obtained per response than Group 4, and that Group 2 is almost identical to Group 4 in this regard. Thus the high peak forces emitted by the subjects exposed to the sweetness proportional schedules cannot be attributed to lower amounts of reinforcement per response. More specifically, in terms of amount of reinforcement available per response, Group 3 and Group 4 are identical; nevertheless, (if the less conservative answer to question 4 of Table 5 is allowed) Group 3 pressed significantly harder presumably because

Table 5

Intergroup Comparisons by the Method of Planned Comparisons for
Selected Variables for Final Three Sessions Combined of Phase II

	Mean F_p	With #8 (conservative)	Without #8 (less conservative)
1 Did reinforcement operations differentially influence mean F_p ? (overall F test)		Yes, $p < .05$	Yes, $p < .05$
2 Are Groups 2 and 3 together different from Group 4 in mean F_p ?		Yes, $p < .05$	yes, $p < .01$
3 Is Group 4 higher in mean F_p than Group 1?		No, $p > .10$	No, $p > .10$
4 Is Group 3 higher in F_p than Group 4?		No, $p > .10$	Yes, $p < .05$
5 Is Group 2 higher in mean F_p than Group 4?		Yes, $p < .01$	Yes, $p < .005$
Reinforcement per Response (mg/R)			
6 Did the reinforcement operations differentially influence reinforcement/response? (F test)		Yes, $p < .01$	Yes, $p < .01$
7 Does Group 3 differ from Group 4 in reinforcement/response?		yes, $p < .05$	Yes, $p < .02$
8 Does Group 2 differ from Group 4 in reinforcement/response?		No, $p > .10$	No, $p > .10$
Reinforcement Rate (mg/min)			
9 Did reinforcement operations influence differentially reinforcement rate? (F test)		Yes, $p < .01$	Yes, $p < .01$
10 Does Group 3 differ from Group 4 in reinforcement rate?		Yes, $p < .05$	Yes, $p < .02$
11 Does Group 2 differ from Group 4 in reinforcement rate?		No, $p > .10$	No, $p > .10$
Rate of Responding			
12 Did the reinforcement operations differentially influence response rate? (F test)		No, $p > .10$	No, $p > .10$

Figure 8. Average amount of sucrose (in milligrams) obtained per response as a function of Phase II conditioning. Each data point is the group mean of individual subject means for three sessions. That is, the total amount obtained in a session was divided by the number of responses emitted during that session. The mean of three sessions was obtained for a given individual. Then these values were combined to obtain a group mean.

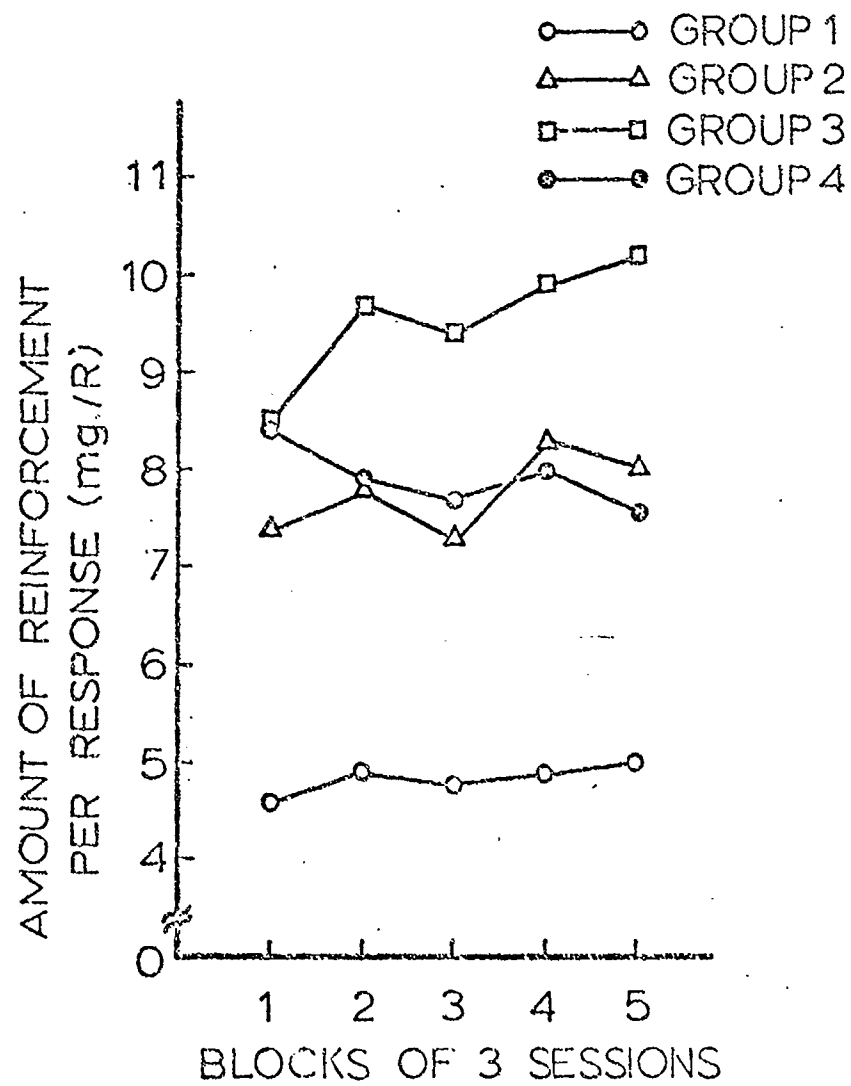


Figure 9. Average reinforcement rate as a function of Phase II conditioning for the four experimental groups. Each point is a group mean of individual subject means computed over three sessions. The reinforcement rate for a single subject was obtained by dividing the amount of sucrose (in milligrams) procured in a session by the session time (measured to the nearest .016 min.).

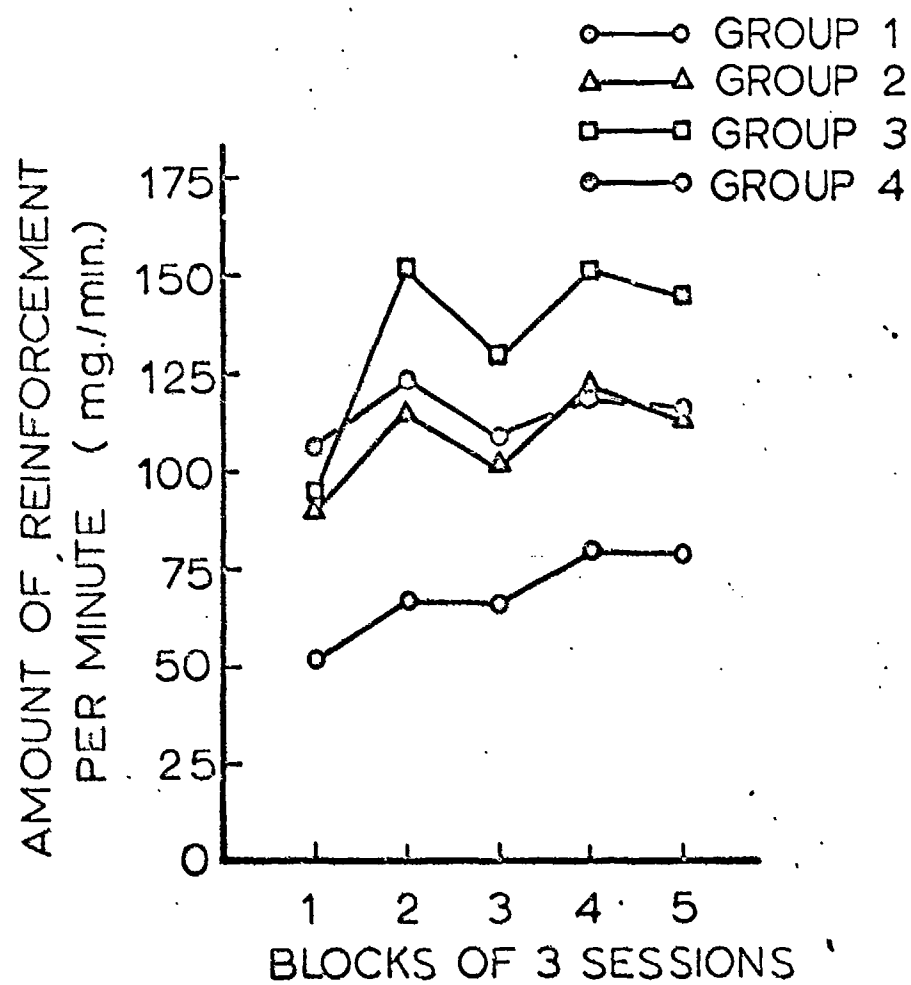
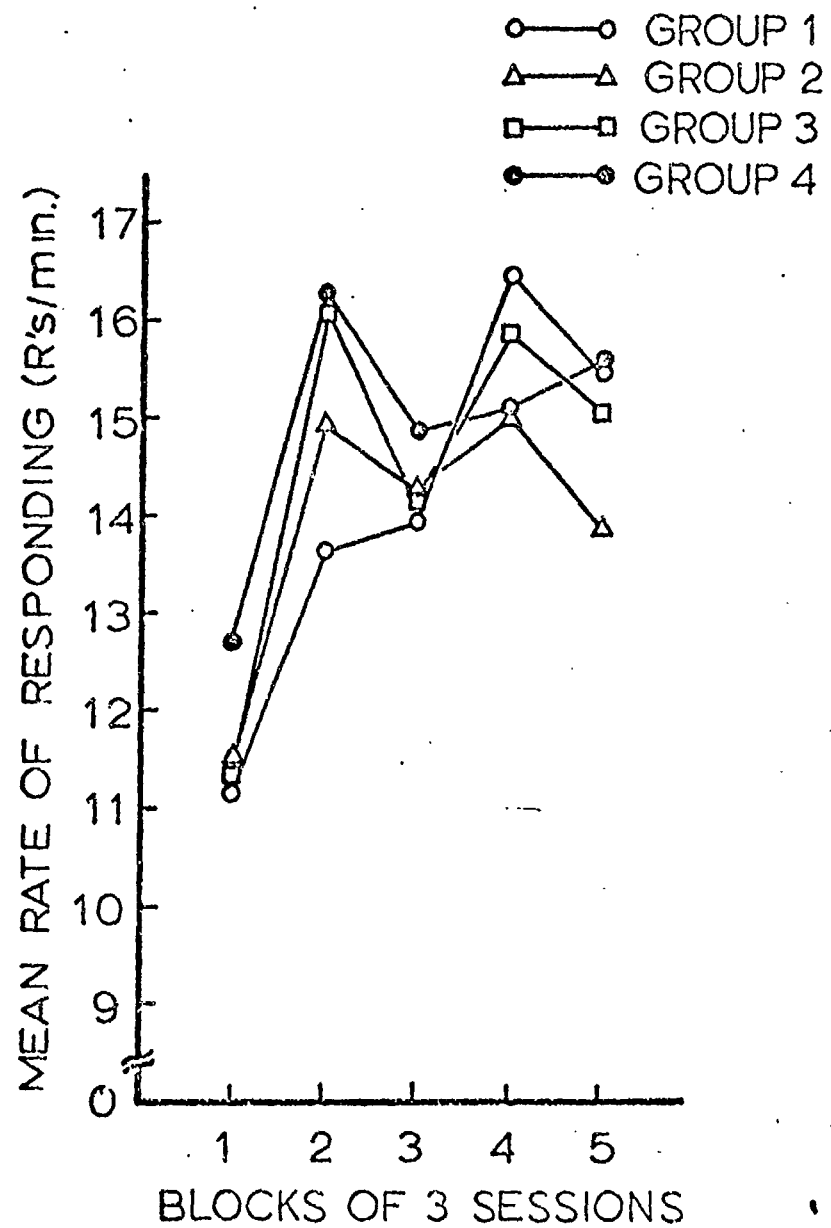


Figure 10. Average rate of responding as a function of Phase II training. Each point is a group mean of individual subject means computed for three sessions. Rate of responding was obtained by dividing the number of responses emitted in a session by the session time.



of the correlation of greater sweetness with higher peak force of response.

It might be argued that the high forces of Group 2 and Group 3 are a manifestation of "drive induction" (Sheffield, 1966). This interpretation seems unlikely in view of the results presented in Chapter 2. It will be recalled that two independent groups of rats separately received two different concentrations of sucrose reinforcement. But there were essentially no differences between the groups - neither in mean peak force nor in rate of responding.

The similarity in mean F_p for Group 1 and Group 4 (non-rejection of null hypothesis, item 3, table 5) is in accord with the previous investigations which have attempted, and failed, to demonstrate the upward shaping of response intensity (either F_p or time integral of force) by use of quantity of reinforcement. The present results show that even when very small absolute quantities are the basis of the proportional reinforcement schedule, rats, on the average, do not press harder to obtain more of the same substance. It is logically clear that this negative conclusion should be limited to the parametric conditions represented by previously used continuous and five-step proportional schedules. Other quantitative arrangements could, of course, produce different results.

Reinforcement rate was significantly influenced by the reinforcement schedules (item 9, Table 5). This result is to be expected in view of the joint occurrence of high forces for

Group 2 and Group 3, and the lack of reliable differences in average rate of responding among the four groups. Thus the significant intergroup differences in reinforcement obtained per response and in reinforcement rate are accounted for primarily by the more forceful bar pressing of the sweetness proportional groups. As expected, mean F_p and amount of reinforcement per response are highly correlated for Group II ($r = .741$, $p < .05$) and Group III ($r = .800$, $p < .05$).

As an overall conclusion it may be stated that the cueing of response force with concentration of sucrose results in more forceful responding. On the other hand, when increased amounts (without the taste cue) are associated with higher forces the rats, on the average, do not press harder. However, both experimental procedures lead to considerable individual differences, so that both types of groups include subjects which seemingly do press harder and subjects which do not differ from regular reinforcement control animals.

Chapter 4

Some Effects of Gain on Force of Bar Pressing

The previous chapter argued that rats, on the average, will exert relatively more force to obtain relatively sweeter reinforcements. The present chapter aims to extend the proportional reinforcement procedures to an examination of the role played by specified gain in determining level of F_p attained.

In a broad sense specified gain is simply the ratio of "payoff" to "exertion." Thus gain can be directly controlled either by adjusting the exertion requirement or by changing the amount of payoff (or both). Notterman & Mintz (1965) coined the term "specified gain" in order to describe quantitative differences among the proportional reinforcement schedules used in their studies. (In this discussion gain and specified gain will be used interchangeably.) However, it seems clear that the notion of gain is implicit in any experimental work which uses either exertion requirement or obtained payoff as independent variables. Generally speaking, most of the previous research has tended to emphasize either one or the other of these variables. For example, Skinner (1938) demonstrated that increasing the FR requirement would eventually bring about a cessation of responding, regardless of whether the response was bar pressing or wheel running; he did not attempt to extend the upper limit of FR responding by using larger or more preferred rein-

forcements. Another more recent example, is Chung's research (Chung, 1965). He varied the force requirement for microswitch closure by pigeons and found that rate of response declined with the higher force requirements. However, Chung did not observe the effects of quantitative variations of reward on this functional relationship. Similarly, the many studies (see Chapter 1, Table 1) concerned with amount of reinforcement usually have not attempted to change the exertion requirements, although Logan (1960) has studied the effects of pitting delay of reward against amount of reward.

The exploratory work reported by Notterman & Mintz (1965, Chapter 11) was an attempt to encompass both aspects of the gain variable. These researchers used a single group of rats and exposed them to successive force proportional schedules, in which number of pellets obtained varied with exertion. However, the minimum force required for some reinforcement was always 8.0 gm. The general result of the study was that increasing the gain served only to decrease the level of F_p emitted. This occurred probably because the increase in gain made available much more reinforcement per response (for a given response distribution this would also increase the amount obtained per response), and because the minimal force requirement was quite low. Moreover, in terms of increased forces for greater amounts of reinforcement, the rats showed no responsiveness to the proportional reinforcement. These investigators concluded that

the values of specified gain (i.e., an index based on the mean of the individual ratios of amount (mg.) of reinforcement to force requirement at each of the steps of a particular proportional contingency) were so high that there was no particular advantage to the animal in responding differentially to the specified gain values used.

In view of this previous work, it seems clear that if the gain variable actually is important in controlling response force, then the dynamic range in which it operates is bounded by the extremes of zero reinforcement on the one hand and an impossible exertion requirement on the other. Further, if specified gain does, at some point, influence force of response, it may well lie below the values used by Notterman & Mintz (1965). Thus, choice of the appropriate quantitative conditions may be crucial if the supposed effects of gain are to be observed. The search for suitable parameters is hindered by a lack of precise psychophysical scales for intensive measures of responding. The particular values of concentration of sucrose and force requirements used in the present work represent educated guesses, the "education" deriving primarily from the previous chapter. The gain values for Group 2, Group 5, and Group 6 shown in Table 6, seem to provide sensible jumping-off places for a quantitative assessment of gain. A 2-step, discontinuous proportional reinforcement schedule was chosen because it yielded the greatest evidence for the upward shaping of response forces

Table 6
Summary of Experimental Groups and
Associated Reinforcement Contingencies

Phase	Number of Sessions	Group	Force Requirement (gm.)	Concent. of Sucrose & by Weight ²	Concent. Gain	Milligrams of Sucrose	Gain for Quantity	Drive Condition
I	2-4	--	--	8	--	6.35	--	22 hr.
II	15	23 (N=8)	8.0	8	1.00	6.35	.79	22 hr.
			24.0	24	1.00	19.05	.79	
		5 (N=9)	8.0	8	1.00	6.35	.79	
			24.0	32	1.33	25.40	1.06	
III	15	6 (N=10)	8.0	8	1.00	6.35	.79	22 hr.
			24.0	16	.67	12.70	.53	
		5	8.0	8	1.00	6.35	.79	
			40.0	32	.80	25.40	.64	
IV	4	6	8.0	8	1.00	6.35	.79	22 hr.
			40.0	16	.40	12.70	.32	
		5	40.0	8	.20	6.35	.16	
		6	40.0	8	.20	6.35	.16	
V	1	5	40.0	8	.20	6.35	.16	46 hr.
			40.0	8	.20	6.35	.16	
		6	40.0	8	.20	6.35	.16	
			40.0	8	.20	6.35	.16	

Notes:

1. A session consisted of 50 reinforced responses regardless of the number of each kind of reinforcement obtained.
2. Volume of reinforcement was held constant at .05 ml.
3. This group was run in the previous experiment. The design is reproduced for easy reference.

in the previous chapter (see Fig. 7, Chapter 3).

Because of the almost infinite number of possible quantitative arrangements, and because of the limited recording capability of the apparatus, the restricted extent of the present study of gain places it in the category of exploratory or pilot research. For this reason, the several combinations of force and concentration of sucrose were tried for the same groups of rats, and thus the experiment does not fit neatly into conventional designs. As a consequence, the description of the specific procedures and the accompanying results are discussed chronologically with some notice being given to the performance of individual animals at each phase. Table 6 summarizes the various phases and the associated conditions. The specific empirical question to which this chapter addresses itself is: Does the specified concentration gain influence the extent of high force emission under 2-step proportional reinforcement conditions?

Method

Apparatus

The response recording and reinforcement dispensing apparatus was identical in all respects to the equipment described in the previous chapter.

Subjects and Procedure for Phase I

The subjects were 20 rats comparable in weight, sex, strain, supplier, and deprivation conditions to the subjects described in the previous chapter.

phase I, which consisted of shaping of the bar-press response, was carried out as described in the preceding experiment. The rationale for using this procedure was given previously. Subsequent to Phase I the subjects were randomly assigned to two groups of 10 each. One animal of Group 5 died toward the end of the experiment, so none of its data are included in the analysis.

Results and Discussion on a Phase-by-Phase Basis

Phase II

From Table 6 it can be seen that the force requirements for Group 5 and Group 6 are identical to those for Group 2 of Chapter 3. Each of these three groups differ, however, with respect to the gain of the higher force requirement and, therefore, with respect to the gain of the schedule as a whole. If the gain of the schedule is important in determining the extent to which rats tend to press harder to obtain sweeter rewards, then one would expect these three groups to display significant intergroup differences in F_p and rank themselves in increasing mean F_p as follows: Gp. 6, Gp. 2, and Gp. 5. Conversely, lack of reliable differences would imply that the gain is really not very important in the present context, or that the parametric conditions were poorly selected.

Phase II consisted of 15 consecutive daily sessions so that Group 5 and Group 6 would be closely comparable to Group 2 in terms of amount of training.

Plotted in Fig. 11 are the mean F_p curves for Group 5 and Group 6. In Table 7 are the individual subject means and standard deviations of F_p for the initial and final sessions of Phase II. Both groups display levels of mean F_p similar to those of Group 2, suggesting that Group 5 and Group 6 were affected in an upward direction by exposure to the proportional reinforcement, as was Group 2. (That is, the forces remained higher than the control groups throughout Phase II.) However, a one-way analysis of variance conducted on these three groups for the last three sessions combined of Phase II yields a non-significant $F(2, 24) = 1.0315$. The implication is that the differences in gain were insufficient to produce reliable differences among the three groups in terms of mean F_p of response. Nor were there any significant differences among these three groups in rate of responding (see Fig. 12). Here also a one-way analysis of variance resulted in an unreliable $F(2, 24) = 0.5104$. However, the forces were distributed in a manner that did result in significant intergroup differences in rate of reinforcement, $F(2, 24) = 7.2651$, $p < .01$. This latter finding is a natural consequence of the similar behavior of the three groups with regard to force and rate. All three groups were taking advantage of the proportional reinforcement to approximately the same degree, and the differences in reinforcement rate simply arose from the different amounts available under each reinforcement contingency.

Figure 11. Mean F_p as a function of the four experimental phases. Each point is the group mean of the individual subject means for a single session. Compare the "curves" of Phase II with those plotted in Fig. 7, Chapter 3.

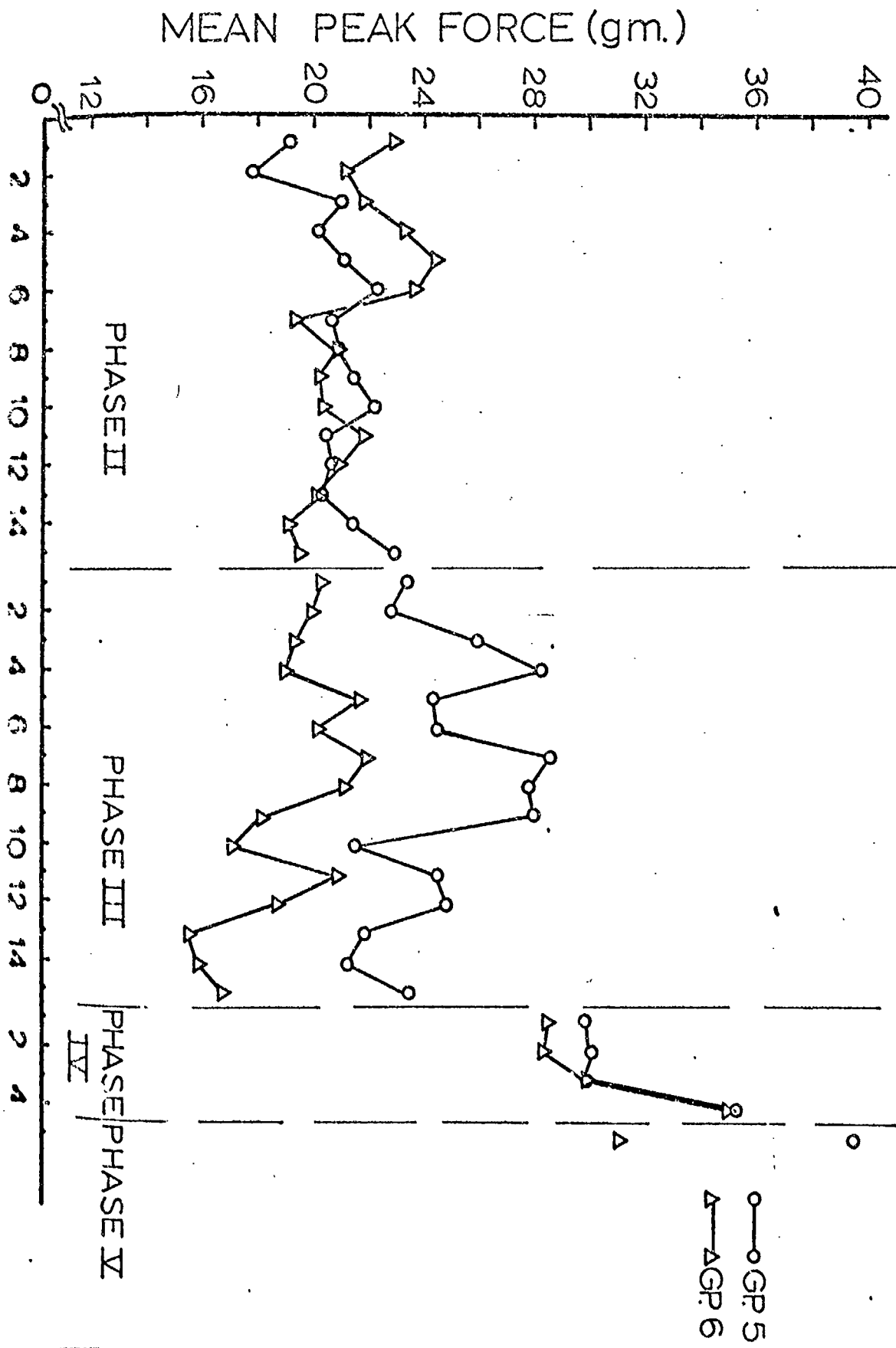


Table 7

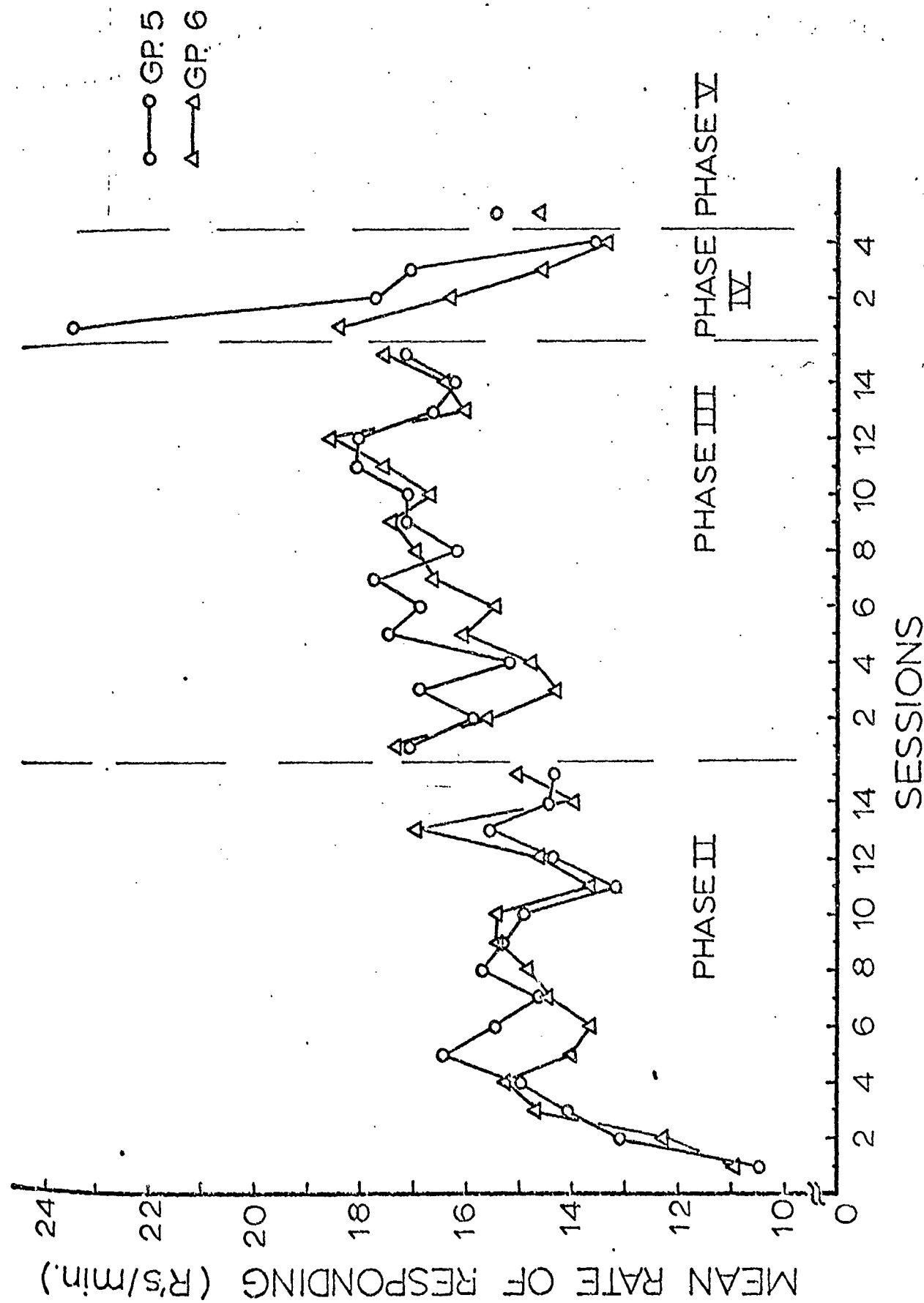
Mean and Standard Deviation of F₂ and Number of Responses
for Initial and Final Sessions of Phase II

Group	Subject	Initial			Final			t
		Mean	S.D.	N	Mean	S.D.	N	
2 ¹	5	22.0	16.0	193	19.3	14.3	198	-1.728
	11	14.6	11.0	229	32.5	16.8	166	11.978****
	13	17.7	9.4	186	16.3	7.4	181	-1.569
	14	15.8	13.6	236	28.2	32.2	233	5.406***
	15	20.1	13.6	205	24.0	20.8	225	2.311*
	23	26.1	22.3	189	30.3	23.6	155	1.706
	30	23.1	19.9	201	27.7	33.5	237	1.795
	33	11.1	8.6	268	11.1	4.2	187	-0.098
	Mean	18.8			23.7			
5	42	16.5	15.3	236	22.8	19.4	229	1.816
	43	15.8	13.7	248	27.9	15.8	186	8.405****
	44	15.8	12.4	200	16.2	9.0	197	0.368
	47	18.4	11.1	188	24.4	17.4	203	4.094***
	48	14.4	7.7	180	20.4	10.8	167	5.889***
	57	25.5	20.4	185	14.8	10.8	232	-6.448****
	59	22.3	17.1	197	15.9	10.6	190	-4.458***
	60	23.0	18.5	220	19.2	10.0	186	-2.670**
	61	21.4	17.0	214	31.8	21.7	178	5.237***
	Mean	19.2			21.5			
6	40	37.6	18.5	157	22.3	12.1	166	-8.769****
	49	19.4	12.7	178	21.2	13.1	166	1.257
	50	15.3	11.0	201	18.4	7.9	163	3.126**
	52	17.4	13.2	215	13.4	8.3	228	-3.769**
	54	21.9	18.1	220	29.2	20.7	192	3.790**
	55	14.6	12.6	266	17.4	9.1	175	2.696*
	56	32.6	16.1	152	12.5	7.2	199	-14.265****
	58	15.7	12.6	246	18.2	12.4	219	2.101*
	62	22.3	16.6	201	19.6	9.4	169	-1.946
	63	22.5	12.8	188	23.5	10.3	164	0.794
	Mean	21.9			19.6			

Notes:

1. These data are repeated from Table 4.
2. "-" means decrease, *p < .05, **p < .01, ***p < .0002, ****p < .000001.

Figure 12. Average rate of responding as a function of the four experimental phases. Each point is a group mean based on the response rate of separate subjects during one session.



Examination of the individual performances suggests, as in Chapter 3, that some subjects simply do not find it advantageous to respond at the higher force levels despite the sweeter rewards which these responses can provide. For instance, number 56 of Group 6 displays a mean F_p similar to that expected for CRF with an 8.0 gm. criterion. On the other hand, some subjects, for example, number 54 of Group 6, clearly seem to be regularly emitting the high forces required for the sweeter solution. These large individual differences again call attention to the possibility that gain may lack sufficient potency to be considered as an important independent variable in controlling response force.

Phase III

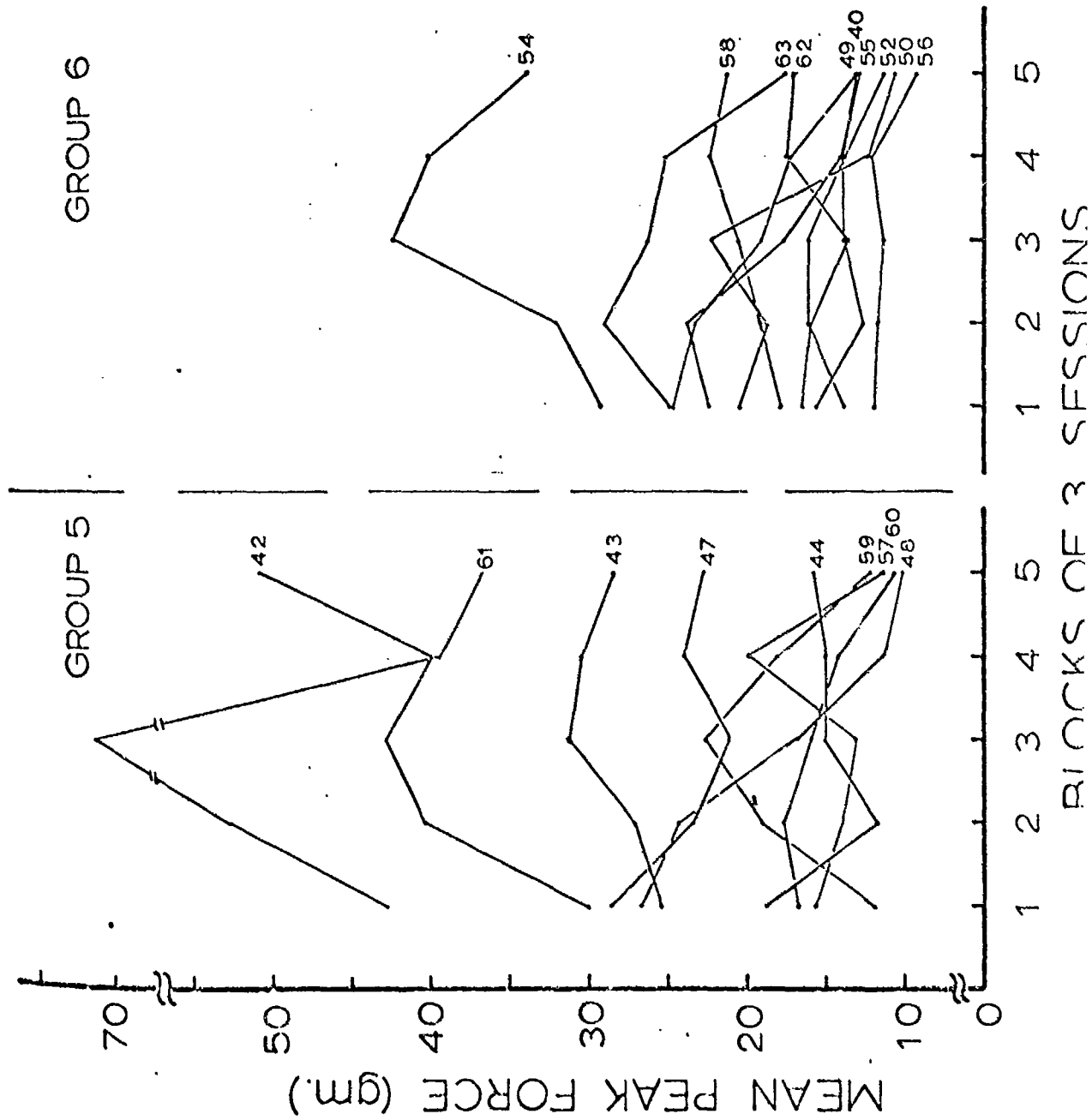
In this phase the gain for both Groups 5 and 6 was reduced, as shown in Table 6, by increasing the higher force requirement. Although, this tactic decreased the gain, it did not influence the relative difference between the two groups. One advantage of manipulating the gain by increasing the force requirement is that it should produce large differences in mean F_p between subjects which continue to press harder to obtain the sweeter solution and those which do not.

Group data for mean F_p of response for the 15 daily sessions of this phase are presented in Fig. 11. Despite the obvious graphic separation, the intergroup comparison of mean F_p is not nearly significant (last session of Phase II),

$p > .10$, Wilcoxon's Rank Sum Test; session 9, where graphic differences are greatest, $p > .10$)². Similarly, rate of response showed no reliable intergroup differences ($p > .10$, see Fig. 12). In view of the individual differences displayed previously, it seems plausible that the group curves may actually represent the lumping together of two more or less separate populations within each of the groups - one of these populations pressing to get the sweeter solutions, the other not. This possibility suggested that a plot of the individual "learning curves" for mean F_p for Phase III might be illuminating. Accordingly, these data are shown in Fig. 13. If the higher gain schedule is having an effect on mean F_p and if responsiveness to proportional reinforcement is displayed in an all-or-none fashion, then one would expect the influence of gain to make itself manifest in terms of a relatively greater number of subjects showing high forces with comparatively high gain. This hypothesis appears to be borne out by the data, but not dramatically. Three subjects in Group 5 (numbers 42, 43, and 61)

²Non-parametric statistics are used in this and the subsequent phases because of the large differences in variance between the two groups in mean F_p . By the Seigel-Tukey non-parametric variability test (Wilcoxon & Wilcox, 1964), Group 5 is more variable than Group 6, $p < .02$. This points up the inappropriateness of a t test. Even with non-parametric procedures the problem of multiple application of tests to the same data cannot be avoided. Thus the intergroup comparisons are to be interpreted cautiously, for each successive test weakens the level of confidence in an unspecified way (see Hays, 1963).

Figure 13. Mean F_p for individual subjects as a function of Phase III conditioning. Each curve is labeled with the subject number. These curves may be compared with the individual data given in Table 7 for Phase II.



and one subject in Group 6 (number 54) probably were attempting to meet the higher force requirement. However, even if these differences in the number of subjects displaying high mean F_p do represent the effects of the independent variable gain, such small intergroup differences imply that gain, as operationally defined here, is not a particularly influential independent variable. All the other subjects were essentially responding as if the 8.0 gm. requirement was the only contingency operative. In fact, these latter subjects displayed substantial decreases in mean F_p during Phase III. By pooling the data of both groups and by comparing the three sessions of Phase II with the final three sessions of Phase III, a rough overall estimate of this tendency to decrease in mean F_p can be made. Wilcoxon's signed rank test applied to the percent change in mean F_p does give indication of a reliable decrease ($p < .05$).

In one sense, the general downward trend in mean F_p can be interpreted as gain "optimizing" behavior simply because the highest gain value represented in either proportional schedule is 1.0 for the lower force step, as opposed to .80 and .40, which are the gain values of the higher force steps for Group 5 and Group 6 respectively. As a cautionary note, it should be recalled that the numerical values for gain probably do not fairly represent the "real" situation as experienced by the rat. Thus the downward trend may be a reflection of a least effort effect. How-

ever, this view would not explain why three subjects in Group 5 and one subject in Group 6 pressed at the higher levels. The forces of these subjects are so high that their occurrence seems to be beyond that plausibly accounted for by random variation alone. A possible resolution to this dilemma hinges on a supposition that the upper force requirement was simply beyond the physical capacity of the majority of subjects.

(During the shaping phase, however, most subjects did emit a few forces of such magnitude.) Perhaps, they gradually came to respond "efficiently" to the only contingency actually available to them, i.e., the 8.0 gm. criterion. The validity of this alternative conjecture is examined in Phase IV.

Phases IV and V

In these phases both groups were switched to the regular reinforcement schedule (as opposed to proportional reinforcement) as shown in Table 6. The only responses which received reinforcement (.05 cc. of 8% sucrose) were those equal to or above 40 gm. Use of this schedule in the present context should help determine whether the performances of the previous phase were a result of a physical incapacity to press with responses of at least 40 gm., or whether the general decline in forces was dictated by the relative attractiveness of the gain at the lower requirement (which in this case is indistinguishable from a tendency for the animals to exert "least effort" compatible with at least some reinforcement.)

Three subjects (one in Group 5 and two in Group 6) showed signs of extinction during the course of Phase IV. But the remaining subjects increased their forces to meet the new requirement a large proportion of the time (Wilcoxon's Signed Rank Test, based on mean F_p of subjects responding at the end of Phase IV, $p < .05$ and $p < .02$ for Group 5 and Group 6, respectively). Therefore, the 40 gm. requirement probably does not pose an impossible task for the majority of rats; however, it may be very close to the exertion level which will just barely maintain responding.

Accompanying the shift to Phase IV was an increase in rate of responding though not quite a reliable one (Wilcoxon's Signed Rank Test for both groups combined, $p < .10$). However, as training on the 40 gm. criterion ensues and as forces increase, there is a very large decline in rate of responding (Wilcoxon's Signed Rank Test for both groups combined, $p < .01$). At first glance, these data seem to be compatible with the results for pigeons reported by Chung (1965). Indeed, if there is a genuine tendency for mean F_p and rate of response to be negatively related, then one would expect such an effect to manifest itself, on a within group basis, in the form of a significant negative correlation coefficient. Accordingly, Spearman's rank correlation coefficient was computed for the fourth session of Phase IV, the result, $r_s = -0.6205$, being significant at the .01 level of confidence. (The three animals which essentially

extinguished were not included in this computation.) Two factors contribute to this negative relationship between rate and mean F_p . First, the number of sub-criterion responses (those between 2.5 and 39.9 gm.) decreased as the level of F_p increased during Phase IV. Second, the high forces appear to bring about a general slow down in responding perhaps stemming from fatigue.

It is possible that the individual cases which extinguished during Phase IV did so simply because of the drive operations used. To check on this eventuality the subjects were not fed following the fourth session of Phase IV. The effects of the drive shift were observed on the following day which was the single session devoted to Phase V. Rate of responding increased for the individuals which had almost ceased to respond during Phase IV; however, their forces showed further decreases suggesting that these subjects could not emit the requisite forces, or if they could, 8.0% sucrose was an insufficient inducement to do so. Excluding these three subjects, overall level of F_p remained essentially unchanged (Wilcoxon's Signed Rank Test, $p > .10$), and rate of response also did not change significantly (same test, $p > .10$), although it did tend to increase. Such a large shift in the drive conditions failed to influence reliably either rate or mean F_p probably because the rats were already very near maximum output by the fourth session of Phase IV.

The data collected during Phases IV and V are particularly

noteworthy in two respects. In the first place it seems remarkable that .05 ml. of 8.0% sucrose can maintain responding on such a high force criterion; i.e., the ratio of payoff to exertion was extremely low. Second, the drive operations of 22 hours of food deprivation appears to have brought about near maximum behavioral output in terms of rate and mean F_p of response.

Taken together, the data from this experiment indicate the following: The results obtained for Phase II suggest that most rats found it "worthwhile" to emit quite often forces above 24.0 gm., regardless of whether 16.0%, 24.0%, or 32.0% reinforced these responses. Since forces between 8.0-23.9 gm. yielded uniformly only 8.0% concentration, the finding emphasizes the behavioral control taken by concentration rather than by gain. However, the presence of the overall downward trends for mean F_p in Phase III suggests that the average subject may consistently choose the higher of two gain values when it is paired with low exertion. Such seems to be the case, even though when required to do so, subjects will regularly emit 40 gm. or more to obtain only 8.0% solutions.

Chapter 5

Feedback during Regularly and Proportionally Reinforced Responding

Experimental psychology has as one of its tasks the elucidation of laws controlling behavior. The word "control" immediately suggests that certain aspects of experimental psychology can be regarded from a cybernetic point-of-view. (As defined by Norbert Wiener, (1948), cybernetics means communication and control in the animal and the machine. Admittedly, this is an extremely broad definition. In current usage, however, cybernetics connotes a point of view more than it describes a particular area of study). Vital to a cybernetic approach to behavior analysis are feedback models. These extend in degree of formality from mathematical models borrowed from mechanical and electrical control theory (McFarland, 1965), to less structured, verbal and diagramatic schemes (Notterman, 1970). Such models have proved their heuristic value in modern psychology. For example, Smith (1962) has shown that sensory feedback is essential to normal perceptual-motor functioning. In the field of operant behavior, Notterman & Mintz (1965) have demonstrated the utility of viewing certain aspects of bar pressing as being dependent on feedback processes. It is the purpose of the present chapter to attempt to develop quantitative descriptions of some of the feedback processes suggested

by Notterman (1970), as well as by the present author.

In Fig. 14 is a diagram which depicts three, more or less distinct, feedback loops which may be important during a session of bar pressing for food on an isometric silent manipulandum. One of these loops, which is represented by the connections between the blocks labeled A, B, and C, is primarily intra-organismic. That is, the loop is physically continuous and is constructed of nerves and muscles. Quite simply, this feedback allows the organism, while responding, to make use of sensory information which is generated by the response itself. The data collected in the previous chapters and analyzed in the present one are relevant to this particular loop, but do not afford a precise description. The two loops which include extra-organismic components are the primary concern of the present chapter. The first of these extra-organismic loops can be referred to as a satiation-hunger loop. It is, of course, represented by the food reinforcement feeding back to reduce hunger thereby decreasing the tendency to emit responses (connections among blocks D, E, C, F, and H). A second extra-organismic loop, also involving the consequences of the response, is derived from the idea that reinforcement is a stimulus as well as a drive reducer. (Henceforth, to be called reinforcement-response loop [connections among E, C, and F].) That is, the events following a response may influence a subsequent response independently of drive level. The block diagram in

Figure 14. Block diagram depicting three possible feed-back loops which may be important avenues of information during a session of bar pressing on a silent, isometric manipulandum. Connections among blocks A, B, and C represent an intra-organismic loop, allowing the response-induced feedback to be sensed while the response is being emitted. Connections among blocks H, D, E, C, and F represent the satiation-hunger loop. The lines joining blocks E, C, and F portray the reinforcement-response loop.

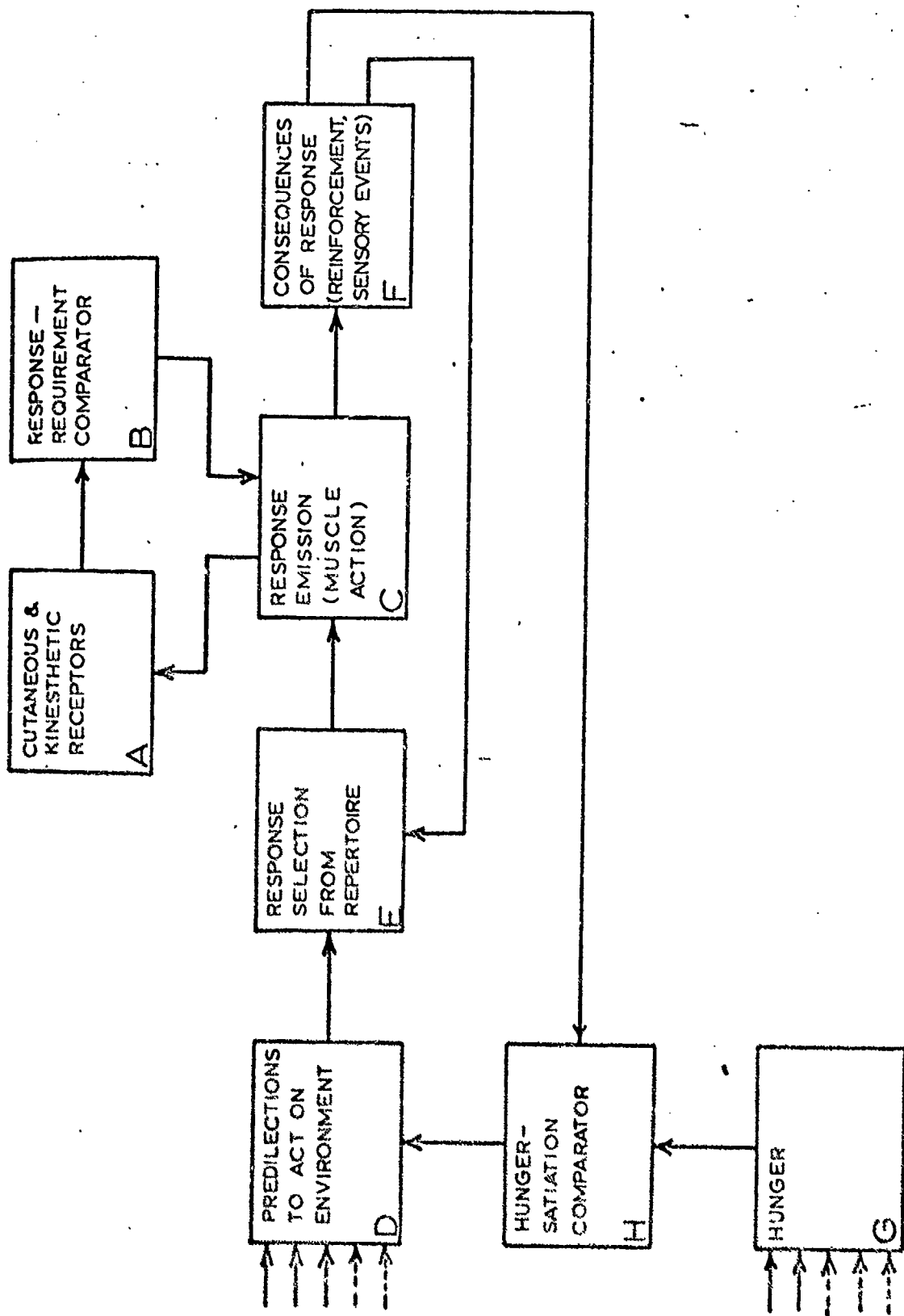


fig. 14 is not to be taken too literally; it is presented for the sake of exposition. Undoubtedly the "real" situation is fantastically more complex than the diagram suggests.

Since this chapter is to examine the loops containing extra-organismic components, it is important to inquire why two such loops are proposed as being necessary. The reason for considering the satiation - hunger loop is straightforward: In many experimental studies using hungry animals it has been observed that rate of responding decreases as the animals procure more and more food. Thus it is natural to ask whether the effect of drive reduction will manifest itself also in terms of another dependent variable, peak force of response.

The rationale behind the second loop with extra-organismic components is not quite as simple. Often, the time rate at which food reinforcement is obtained is high enough to allow the procurement of several reinforcements before any significant, direct drive reducing effects can occur. It is quite possible that the stimulus properties of food--in that they influence taste--can bring about physiological changes, e.g., release of insulin from the pancreas, which may influence the organism's nutritive needs (Valenstein & Weber, 1965). Thus it appears reasonable to posit (conceptually) two separate loops by which the effects of reinforcement influence the rate and intensity of subsequent responses.

The importance of the stimulus properties of reinforcement

in determining mean peak force of response was demonstrated in Chapter 3. Proportional reinforcement (specified in terms of concentration of sucrose) produced higher mean peak forces than amount - proportional reinforcement. However, the extent to which a single reinforcement influences the very next responses has yet to be examined. The typical subject in Group II (8.0 gm. to 23.9 gm. + 8.0%, and 24.0 + gm. + 24.0%), because of variability in response force, obtained sequences of reinforcements in which different concentrations frequently followed one another. Did these discriminably different reinforcements produce "extinction effects" or "amount of reinforcement effects"? That is, from several experiments (Notterman & Mintz, 1965) it is known that reduction of reinforcement to zero amount brings about a rapid rise in mean peak force. Could such a phenomenon on a smaller scale be occurring during proportionally reinforced responding? Does the receipt of an 8.0% solution compare so unfavorably with a 24.0% solution that the rat presses harder after obtaining an 8.0% reinforcement and vice versa? Do any regular, distinguishable patterns develop as a result of such tendencies, leading to a cyclical form of response stereotypy? And are the supposed patterns in early training different from those in later training? Are different patterns correlated with the various reinforcement schedules? Answers to these questions are sought by examining the serial properties of response force emission through the use of spectral analysis.

The Satiation-Hunger Loop

Because of the time required for food to be assimilated and because reinforcements are accumulated over session time, it is reasonable to assume that evidence for the presence of satiation might manifest itself in terms of a trend in the peak forces emitted during a session. Thus linear regression analysis was applied to the session peak force records of Phase II for all subjects of the six experimental groups reported in Chapters 3 and 4.

Before the analysis was undertaken, it was necessary to consider the possibility that the peak force distributions may require a normalizing transformation in order to conform to the assumptions underlying parametric statistical tests. In Fig. 15, mean peak force is plotted as a function of standard deviation of peak force for the individual subjects of all six groups. It is clear that there is a strong relationship between mean and standard deviation. (Correlation coefficients computed for each group separately are of comparable magnitudes.) Given this robust association and the fact that force (when considered as a scalar) is an essentially positive quantity (see Jenkins & Watts, 1968), a \log_{10} transformation was tried. Figure 16 shows that the transformation was partially successful in reducing the correlation between the mean and standard deviation. In view of the moderate success of taking logarithms, no other transformation was attempted, and the linear regression

Figure 15. Scatter plot of mean F_p and standard deviation of F_p . Each point is based on the total distribution of responses for the final three sessions of Phase II. Data for all the subjects of Groups 1 through 6 are plotted.

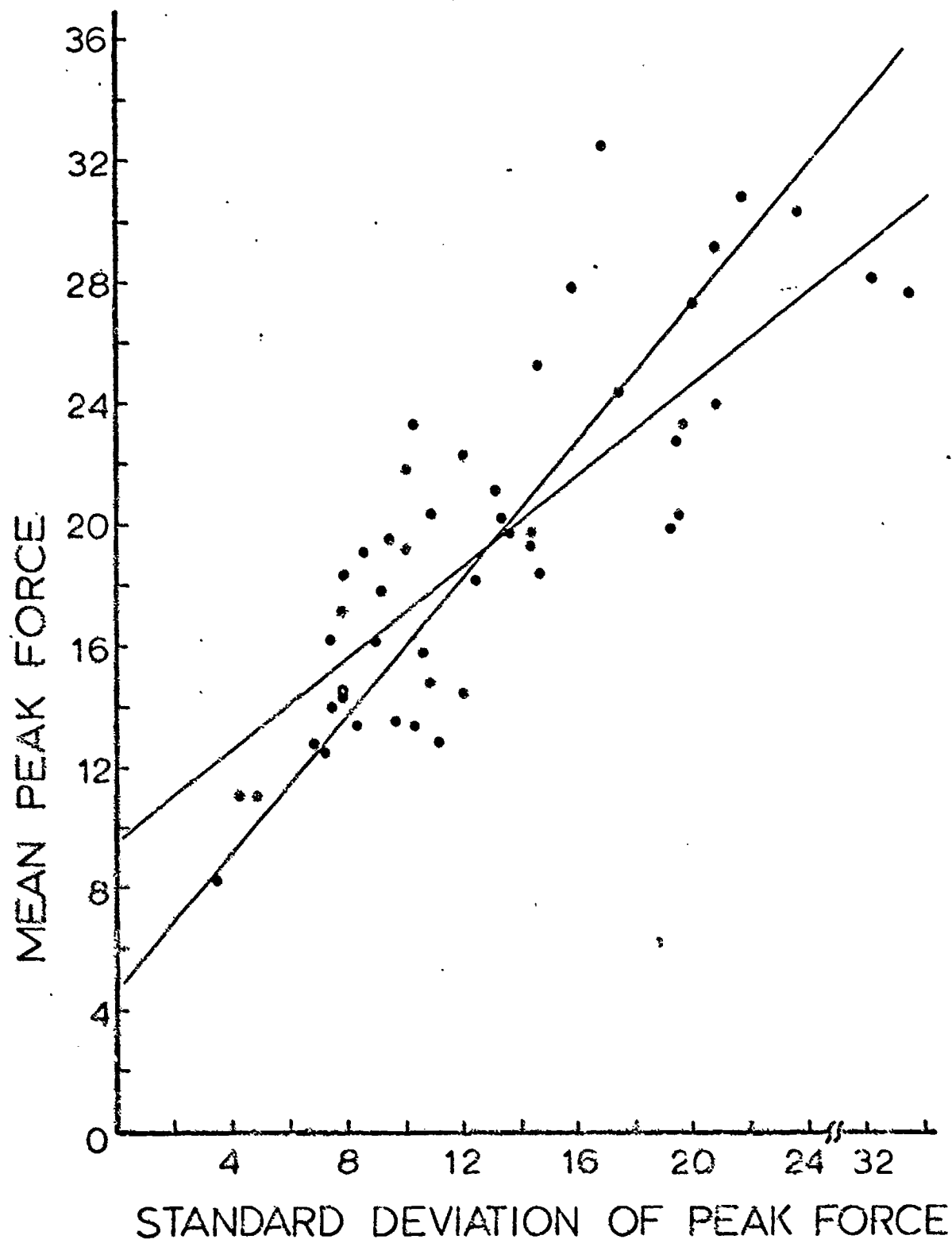
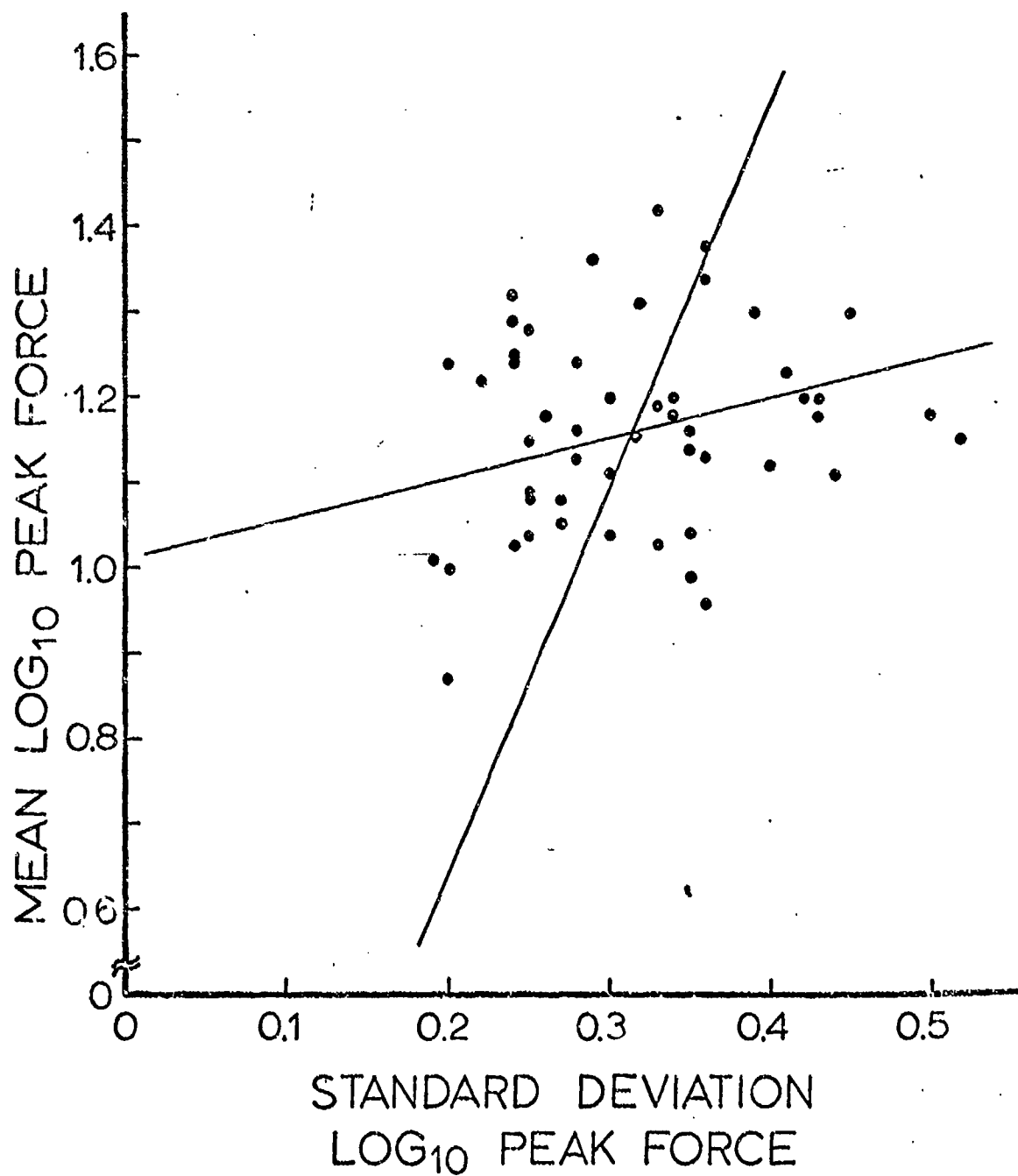


Figure 16. Scatter plot of the mean and standard deviation of the \log_{10} transformed peak force distributions for the last three sessions of Phase II. Data for all subjects in Groups 1 through 6 are presented.



analysis was conducted on the \log_{10} transformed scores.

The observed relationship between mean and standard deviation can be explained in a number of ways: From a psychophysical viewpoint the association is a natural consequence of Weber's law. Or one could argue that low magnitude responses have been reinforced in the past, especially during the shaping phase, and as a result are emitted occasionally, thereby inflating the variance when the rat is responding at relatively high force levels. This latter type of interpretation is similar to Skinner's (1938) concept of the reflex reserve and Keller & Schoenfeld's (1950) idea of response subclasses.

Regression coefficients of F_p on ordinal position are presented in Table 8. It is immediately obvious that the coefficients are quite small with most of the slopes being very near zero. If there were some slight reliable trend, one would expect the mean regression coefficient for a particular group to differ significantly from zero. Accordingly, this hypothesis was tested using the t distribution. Out of the 24 tests carried out, only one was significant at the .05 confidence level which is--of course--what would be expected by t distribution in the absence of any true difference. Thus there is no hard evidence that the data display any reliable linear trends during a session, either early in conditioning or late in conditioning.

The plot of F_p as a function of ordinal position for a typical subject from Group II (Fig. 17) provides a visual demon-

Table 8

Regression Coefficients of $\log_{10} F_p$ on Ordinal Position

Group	Subjects	Sessions of Phase 2			
		1	2	14	15
1	3	.069	.032	.029	.003
	9	.044	-.062	-.007	-.002
	16	-.007	.000	-.018	.018
	17	.026	-.034	.002	.006
	21	-.011	.055	.022	-.011
	29	-.015	-.009	.016	-.040
	35	.036	-.024	.036	.028
	Mean	.020	-.006	.011	.00
2	5	-.032	-.005	.008	.024
	11	-.002	.005	-.026	-.014
	13	-.047	.005	-.016	.015
	14	-.031	-.012	.005	.026
	15	-.014	.004	.000	.000
	23	.015	.067	.000	x
	30	-.056	-.014	-.019	-.002
	33	.024	.013	-.017	.013
	Mean	-.010	.008	-.008	.009
3	1	-.002	.072	.025	-.004
	2	.029	-.065	.019	.003
	6	-.033	-.026	.018	-.018
	8	-.029	-.023	.019	-.004
	20	-.007	.011	-.010	-.017
	28	.030	.003	-.006	-.015
	36	-.027	-.040	.005	-.053
	38	-.006	.005	-.027	-.032
	Mean	-.005	-.008	.005	-.018*
4	4	-.049	-.003	.033	.003
	10	.007	-.037	-.009	-.038
	18	.016	.007	.021	.000
	25	-.037	-.019	-.006	-.018
	26	.019	.031	-.051	-.024
	31	.008	.018	.026	.033
	34	-.031	.005	-.019	.027
	Mean	-.010	.000	.002	-.003

Table 8 (Cont.)

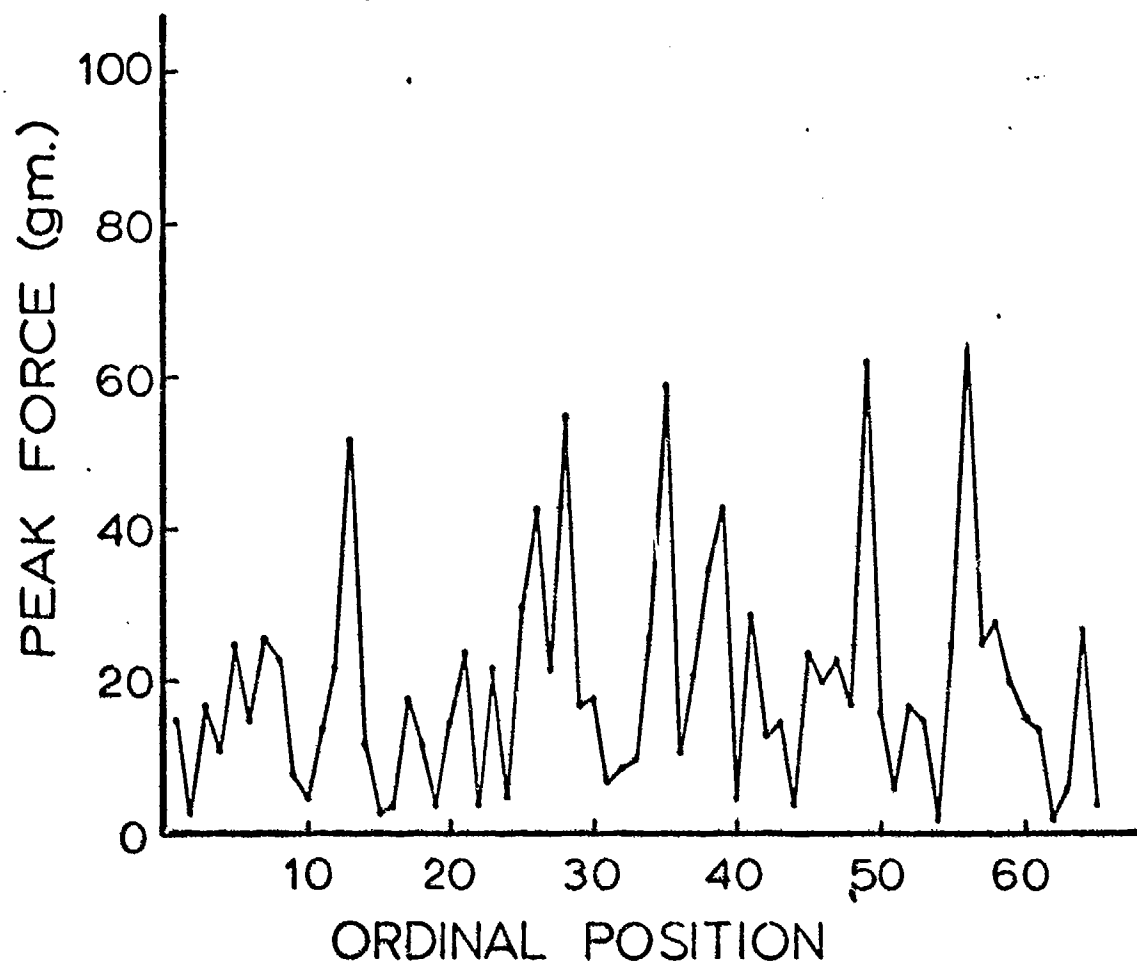
-2-

5	42	.024	.046	.022	.027
	43	.007	-.021	-.021	.001
	44	.005	.010	-.031	.009
	47	-.010	.025	-.026	.030
	48	.010	.000	.019	.012
	57	-.059	-.013	-.022	-.028
	59	-.034	-.048	-.015	-.011
	60	.005	.008	.006	.005
	61	-.008	-.036	.037	.037
	Mean	-.007	-.003	-.003	.009
6	46	.001	.019	.010	.037
	49	-.003	-.035	-.003	.015
	50	-.008	.021	.033	.053
	52	-.002	.001	.018	-.020
	54	.057	-.044	.000	.001
	55	-.021	.010	.037	.001
	56	.032	.026	-.006	.024
	58	-.015	-.005	-.002	.000
	62	-.009	.068	-.036	-.054
	63	.028	.053	.109	.043
	Mean	.006	.011	.016	.010

Notes:

1. * $p < .05$, null hypothesis of zero slope using to the t distribution.
2. "x" data lost in card reader jam.

Figure 17. Peak force of response for one session of responding in Phase II. This subject was in Group 2.



stration of the failure of linear regression to account for an appreciable portion of the variance. The most prominent feature of this graph is the large amount of variability. Are the large changes in peak force correlated with one another and with the type of reinforcement which these responses produce? Do serial correlation and spectral analysis account for any more of the variance than linear regression? Or are the observations essentially uncorrelated? These questions are examined in the next section.

The Reinforcement-Response Loop and Spectral Analysis

Since Abelson's (1953) pioneering efforts to apply spectral analysis to psychological phenomena, great strides have been made in the general development of these analytic techniques. The physical and information sciences have benefited from these improvements more than has experimental psychology. However, in recent years there have been a few attempts to use spectral analysis on data gathered from experiments emphasizing psychological variables (e.g., Weiss, Lattes, Siegel, & Goldstein, 1966). Subsequent to Abelson's dissertation several excellent books have been written which make spectral analysis accessible to the non-mathematician (see, e.g., Blackman & Tukey, 1958; Bendat & Piersol, 1966; Fishman, 1968; and Jenkins & Watts, 1968). In view of the extensive mathematical treatment this topic has received, the author will make no attempt to give a detailed explication of Fourier analysis and its statistical

counterpart, spectral analysis. Rather, for the sake of brevity and ease of communication, the explanation is developed on a verbal and graphic basis.

Spectral analysis is a type of time series analysis which attempts to discover and describe the periodic tendencies of a time-based process. In the experimental sciences, one frequently encounters data which consist of measurements ordered in time; these observations as a function of time are known as a "time series." In some cases the data are sufficiently consistent so that a mathematical function can be used as a model for the process. An example of such a process can be represented by a cosine function:

$$y(t) = a \cos (2 \pi f_0 t)$$

where $y(t)$ is the process, f_0 is the frequency of oscillation in cycles per unit time, and a is the maximum amplitude of the process. A well-regulated 60 cps (cycles/sec or hertz) alternating current voltage can be approximated by such a function. The rhythmic variations in voltage can also be described in terms of the period of oscillation, which is the time interval required for the process to complete one cycle. For a 60 cps alternating voltage the period, or the reciprocal of the frequency, is $1/60$ cps or about 16.7 milliseconds. Unfortunately, the time series encountered in a practical research setting are not nearly so well-behaved as the cosine function. Indeed, sometimes, especially in experimental psychology, it is

not at all obvious that an observed series has any orderly aspects. Measurement error and uncontrolled factors combine to introduce random components into the observations of any realizable time series. In many cases, phenomena occurring in time include, to greater or lesser extents, random fluctuations (e.g., a Gaussian process) that can be described by their statistical properties. These are usually called stochastic processes and are characterized by the probability distributions associated with them, known statistically as random variables, $X(t)$. Thus the stochastic process is described by a set of random variables such that for each point in time there is a probability distribution with a given mean, variance, and higher moments. An example of a well-described stochastic process would be the cosine function plus a Gaussian component:

$$X(t) = a \cos (2 \pi f_0 t) + Z(t)$$

where $X(t)$ is the random variable representing the stochastic process, and $Z(t)$ is a Gaussian process. The Gaussian process has a normal probability distribution, and successive observations in time are essentially uncorrelated. It is called white noise by communications engineers.

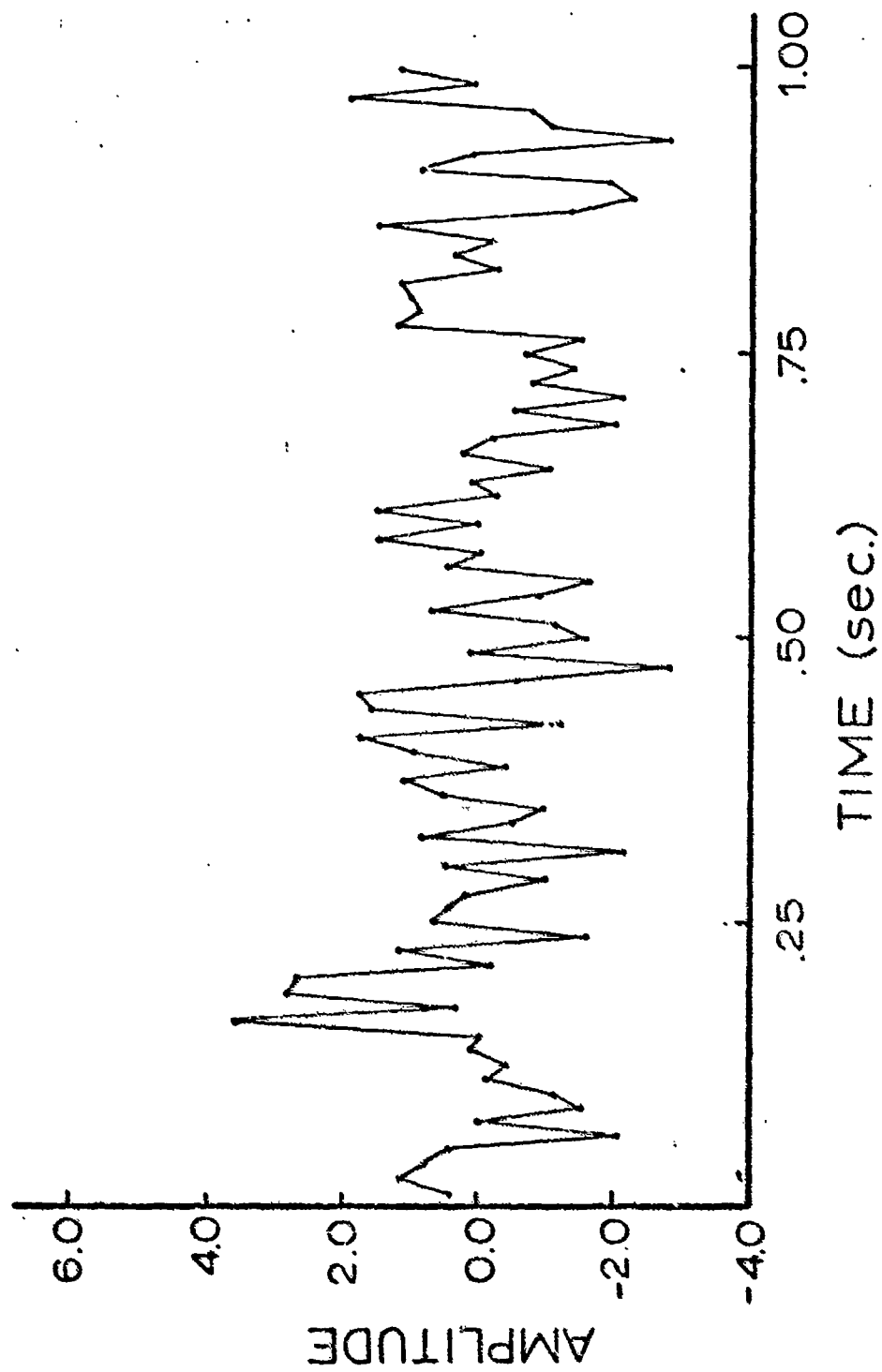
From the point of view of experimental science the usual problem is to detect the orderly (e.g., periodic, rhythmic, patterning) aspects of a stochastic process as well as to describe the probability distributions. On an intuitive level, it seems clear that the relative importance of random fluctuations

can be reduced by averaging the data, thereby separating the "signals" of interest from the "noise." Autocorrelation and spectral analysis are complementary averaging techniques which are powerful tools in extracting the non-random components from a time series.

In Fig. 18 is a particular realization of a stochastic process with the number of observations, $N = 80$. Visual inspection provides few clues for deciding whether any periodicities are present. However, there does appear to be some slowly varying component.

A first step in determining the nature of the non-random component is to estimate an autocorrelation function from the observed time series. Autocorrelation is accomplished by correlating the original series with another series composed of the original one, but moved or slipped in sequence by $0, 1, 2, \dots, K$ observations. The numbers $0, 1, 2, \dots, K$ are called the lag numbers. Therefore, the value of the autocorrelation function at lag 0 is 1.0, which is the product moment correlation of the series with itself. Likewise the value of the estimated autocorrelation function at lag 1 is the correlation of the series with a new series made up of the original original/one, but starting at the second observation. For a discrete time series (i.e., one that is composed of observations spaced in time by an amount Δt ; Δt in Fig. 18 is 12.5 msec.) the autocorrelation is the normalized version of the autocovariance function; The autocovariance function can be estimated by:

Figure 18. A stochastic process with a slowly oscillating component.



$$(1) \quad C_{xx}(K) = \frac{1}{N} \sum_{t=1}^{N-K} (x_t - \bar{x})(x_{t+K} - \bar{x}) \quad K=0,1,2,\dots,N-K$$

where K is the lag number, N is the number of observations, x_t is an observation at time t , and \bar{x} is given by:

$$(2) \quad \bar{x} = \frac{1}{N} \sum_{t=1}^N x_t$$

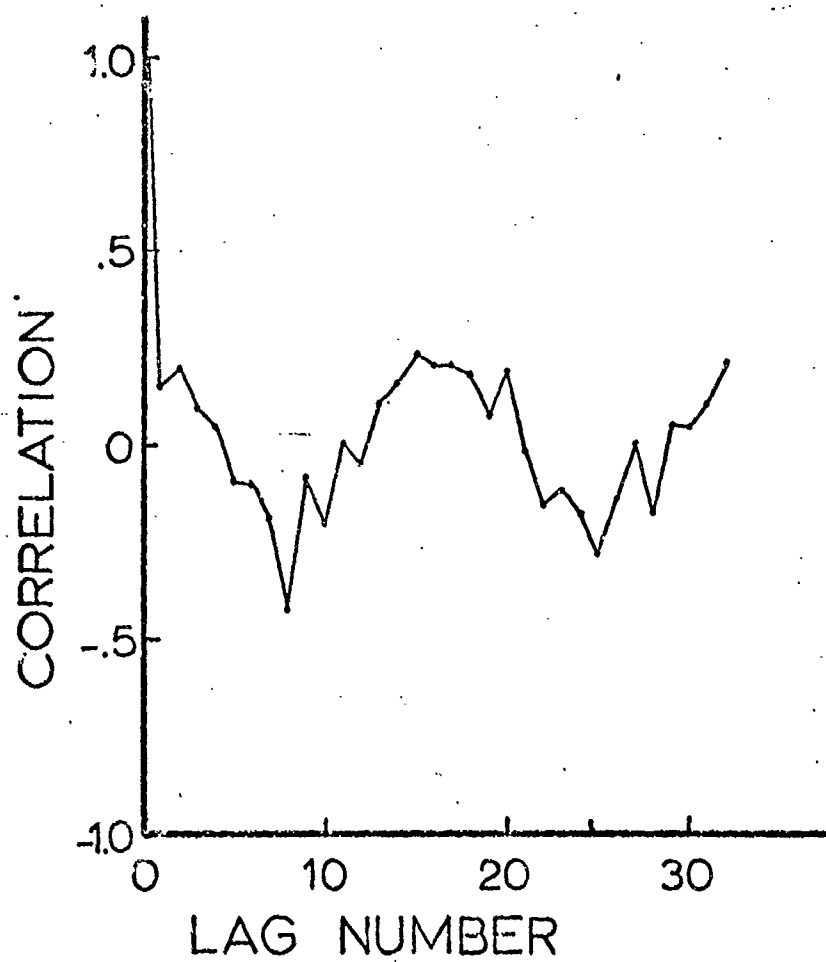
which is the sample mean of the whole series. The autocorrelation is given by:

$$(3) \quad r_{xx}(K) = \frac{C_{xx}(K)}{C_{xx}(0)}$$

One can see that the autocorrelation function is actually the autocovariance function divided by the sample variance of the series. The primary reason for using the autocorrelation function instead of the autocovariance function is that it allows one to compare results obtained from observations based on different scales of measurement.

The estimated autocorrelation function for the time series of Fig. 18 is plotted in Fig. 19. The estimates were computed for $K = 0,1,\dots,32$. There appears to be a slow oscillation in this function; its period is about 15-17 observations, or about 0.189 sec.-0.213 sec. (5.32-4.71 cps). Further, it should be noted that the absolute value of the correlations, on the average, decrease as the number of lags increase. This latter effect is the result of the random components of the original time series, whereas the obvious oscillation in the autocorrelation function is the result of some underlying periodic

Figure 19. Autocorrelation function based on 32 lags.
This function was estimated from the data presented in Fig. 18.



process. Actually the data in Fig. 18 were generated for the purposes of demonstration by a digital computer, according to the following scheme:

$$x(t) = a \cos (2\pi f_0 t) + z(t)$$

where $a = 1.0$, $f_0 = 5.0$ cps or 0.0625 cycles/12.5 milliseconds, $z(t)$ is a sample of white noise with zero mean and unit variance. Thus autocorrelation was, at least partially, successful in extracting the process of interest from the random fluctuations.

For purposes of comparison it is important to note that the autocorrelation function for white noise would be close to zero at all lags. Also the longer the record of normal deviates being examined (i.e., the larger the sample), the closer the autocorrelation function approximates zero, except, of course, at lag 0 where it would still be 1.

The validity of the autocorrelation function in describing a stochastic process depends on the assumption of "weak stationarity" or "covariance stationarity." These equivalent terms represent a degree of statistical stability intermediate between non-stationarity and complete stationarity. A process is said to be completely stationary if and only if the mean variance and higher moments do not change in the long run. The assumption of weak, or covariance stationarity holds when the mean and variance do not change in the long run, but the higher moments may or may not be changing. A process is non-stationary if either or both the mean and variance do not remain constant.

Thus a series of observations displaying an obvious linear trend is non-stationary. The assumption of weak stationarity is sufficient to imply that the autocovariance function depends only on time separation; i.e., since the variance is constant for a given series of observations the covariance terms, of which the autocovariance function is composed, depended only on the structure (if any) of the variations of the individual data points. The cosine plus noise process is (in theory, at least) completely stationary; thus, it is also weakly stationary. If one can assume that a stochastic process is weakly stationary or covariance stationary, then autocorrelation and spectral analysis are valid techniques for describing the process.

The stochastic processes encountered in actual practice are not nearly so orderly as the contrived example. Therefore, it is desirable to have some method for erecting confidence intervals about the autocorrelation function. Unfortunately, adequate procedures for accomplishing this have not been worked out. However, the statistical properties of the sample-smoothed spectral density function (the Fourier transform of the weighted autocorrelation function) are rather well known (see e.g., Jenkins & Watts, 1968).

Before going on to a brief explanation of spectral analysis, it will be necessary to consider the topic of Fourier analysis. Fourier techniques allow one to express time-domain functions in terms of their frequency (cycles per unit time) components.

Transformation from the time domain into the frequency domain is accomplished principally by application of Fourier's theorem, which states that a given analytic function can be approximated to any degree of accuracy by a linear combination of sine and cosine functions. The spectrum of a process or function reveals the way in which different frequencies of oscillation contribute to the variance. The spectrum is the Fourier transform of some function in the time domain. In practice one deals with functions which have a finite extent in time, and are sampled at a spacing Δt in time. These restrictions have a number of effects on the Fourier transform. A finite length record results in distortions in the frequency domain. Loosely speaking, these distortions become worse as the length of the observed series gets shorter. Further, it is generally true that the degree to which peaks in the spectrum can be resolved depends on the length of the record - the longer the record the greater the resolution, i.e., the higher and narrower the peaks become. Sampling observations every Δt units of time automatically limits the upper range of frequencies which can be represented in the spectrum of a realizable process. The highest rate of oscillation that can be detected in any record is $.5 \text{ cycles}/\Delta t$ (Nyquist frequency), since frequencies higher than this go through their oscillations between the points of observation, and thus can only be "seen" as lower frequencies ("aliases").

Special difficulties also arise when Fourier analysis is applied to a stochastic process. The theoretical spectrum for a normal process or white noise is a flat line of zero slope. This seems intuitively reasonable because a continuous range of frequencies is present in white noise and each contributes equally to the variance. Unfortunately, the raw spectral estimates for a normal process do not converge in a statistical sense as the length of the record is increased, although the spectrum does maintain the tendency to have zero slope. However, a smoothed spectral estimator does converge statistically, in that the variance of the spectral estimates decrease as more smoothing is carried out. But smoothing, by increasing the bias, may defeat the very purpose of carrying out the analysis - detection and resolution of peaks. Therefore, when computing smoothed spectra of a stochastic process, one must compromise between variance and bias (stability and fidelity). Jenkins & Watts (1968) suggest an empirical approach to accomplish this compromise. It involves estimating the spectral density function from at least three autocorrelation functions truncated at three different lag values. Smoothing in the frequency domain is equivalent to multiplying the autocorrelation function by a lag window or weighting function. The lag window or smoothing procedure used in the analysis that follows is called the Tukey window (also Tukey-Hanning window) and is given by:

$$(4) \quad w_T(u) = \begin{cases} 1/2 (1 + \cos \pi u/M), & |u| \leq M \\ 0, & |u| > M \end{cases}$$

where M is the number of lags used to estimate the autocorrelation function. (The "window" nomenclature was suggested by Blackman & Tukey, 1958.) It can be shown that the smoothed spectral estimates are distributed approximately as χ^2_ν with the degrees of freedom $\nu > 2$. (See Jenkins & Watts, 1968, Chapter 6.) In general, the number of degrees of freedom associated with a spectral estimate depends on the length of the record, the type of smoothing procedure, and the number of lags used in estimating the autocorrelation function. For the Tukey window the degrees of freedom are given by:

$$(5) \quad \nu = 2.667 \frac{T}{M}$$

where M is the number of lags and T is the length of the record. Jenkins & Watts (1968) present graphs from which the confidence intervals for an estimated spectral density function can be conveniently obtained once the degrees of freedom are known. The bandwidth, b , for the Tukey window is:

$$(6) \quad b = \frac{1.333}{M}$$

It gives an indication of the range of frequencies over which the spectral estimates have been smoothed. Generally speaking, the bandwidth times the variance of the estimate is a constant. Thus a small bandwidth implies a large variance of the estimate

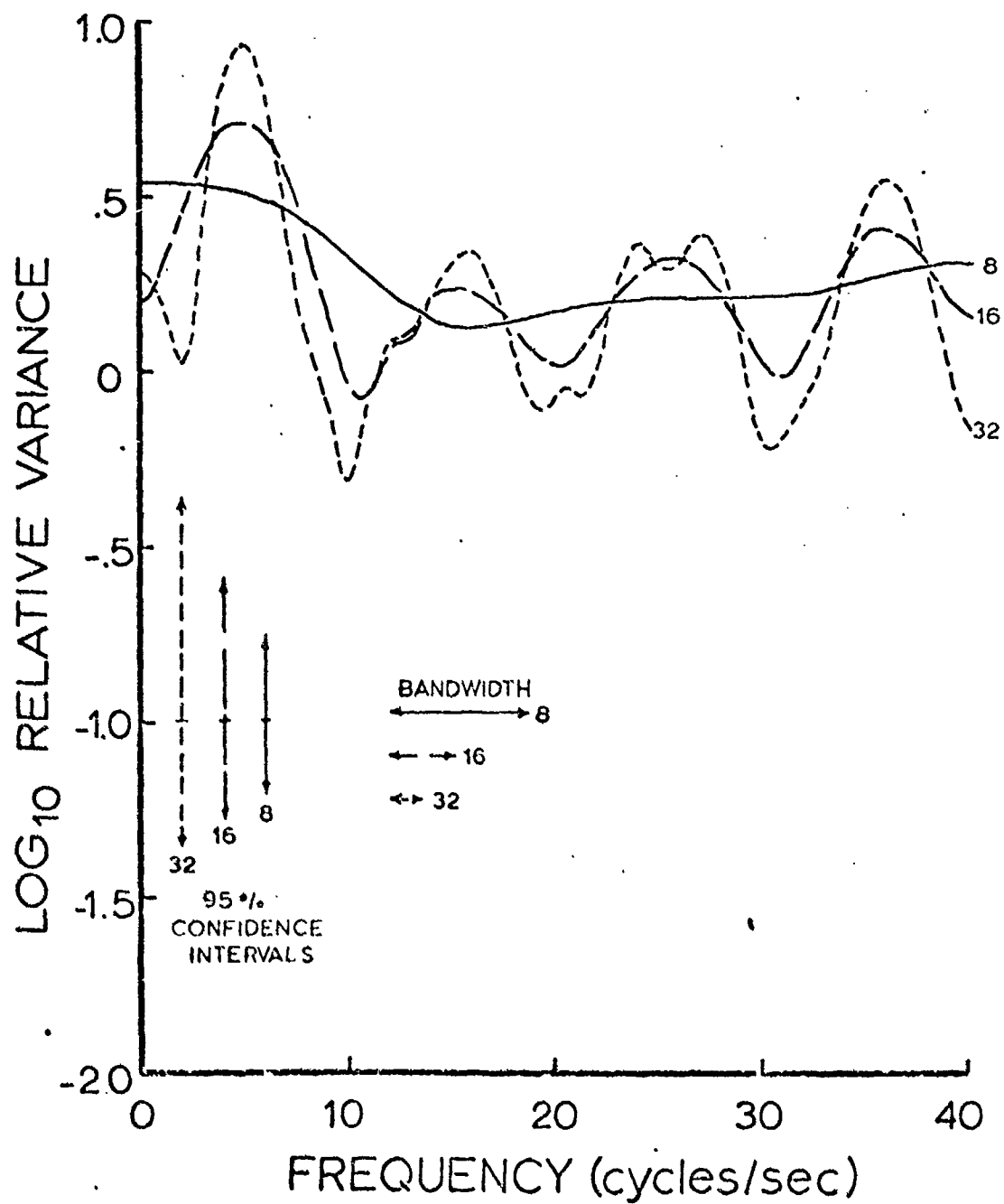
but small bias; conversely, a wide bandwidth means a small variance and large number of degrees of freedom but a large bias. For the Tukey window, estimates which are more than one bandwidth apart are essentially statistically independent.

In Fig. 20 are the estimated, smoothed spectral density functions for the time series in Fig. 18. The estimates were obtained using the formula:

$$(7) \quad S_{xx}(f) = 2\Delta \left[r_{xx}(0) + \sum_{k=1}^{M-1} W_T(k) r_{xx}(k) \cos(\pi k f / M) \right]$$

where $f = 0, 1, 2, \dots, 100$, Δ is the spacing of observations, in this case $\Delta = 12.5$ msec., M is number of lags upon which the autocorrelation functions are based. For very long series it is preferable to use the fast Fourier transform because it considerably reduces computation time (Cochran et al., 1967). Each estimated function is the Fourier transform of the weighted autocorrelation function truncated at three different lag values. (Multiplying the autocorrelation function by the lag window is equivalent to smoothing in the frequency domain.) The reason for estimating three functions might have been anticipated by the foregoing, and should be clarified by the ensuing discussion. For the moment it is important to notice several features of Fig. 20. The range of frequencies extends from 0 to 40 cps, and the smoothed spectral estimates are plotted on a logarithmic scale. The largest peak in each of the three spectral

Figure 20. Spectral density functions of the cosine plus noise process estimated from the autocorrelation function shown in Fig. 19. The numbers labeling each curve are the truncation points of the particular version of the autocorrelation function from which the estimates were obtained. The ordinate represents \log_{10} relative contribution to the variance. The abscissa is frequency of oscillation in cycles per second.

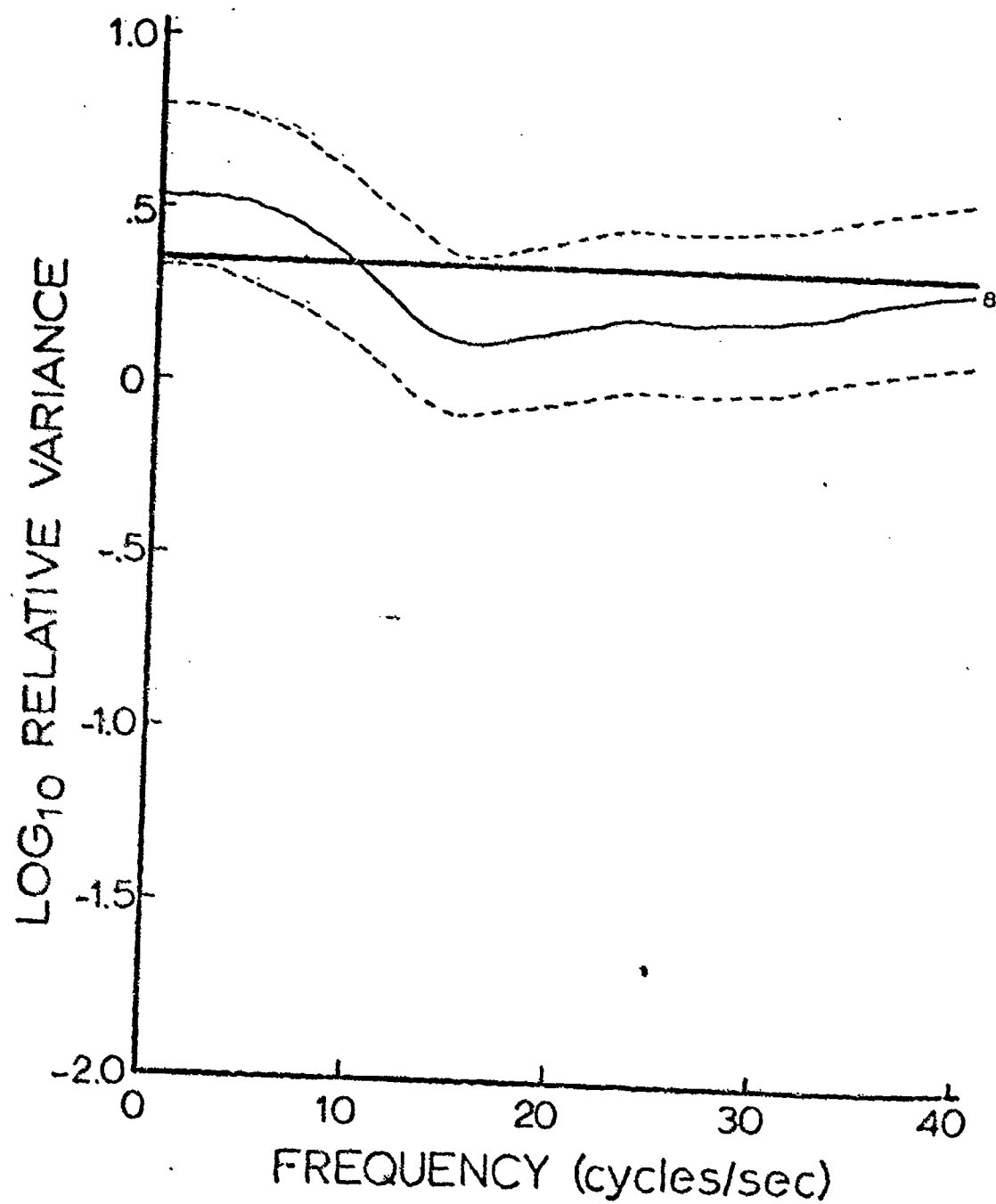


density functions is in the low frequency range. For the functions estimated from 16 and 32 lags the largest peaks are centered at 5.0 cps. This is the frequency of oscillation that was purposely mixed with the random deviates to obtain the original series shown in Fig. 18. The various spurious peaks that appear in the higher frequencies for the 16 and 32 lag functions demonstrate the tendency of the variance of the estimates to increase as the bandwidth is decreased.

The .95 confidence intervals and the corresponding bandwidths for the three functions are also shown in Fig. 20. Reproduced in Fig. 21 is the estimated spectral density function for 8 lags with the .95 confidence interval erected about it. The true spectral density function should lie in this interval 95% of the time. The heavy black line of zero slope represents the spectral density function of white noise. Moreover, it is clear that the true function might be flat. If it were not known in advance that there really is an underlying periodic process (since it was purposely contrived), one would be uncertain as to the true nature of the process.

This uncertainty could be reduced if the process were observed for a longer period of time, thereby increasing the number of observations in the record. Increasing the length of the record has two effects. First, it increases the degrees of freedom, thus tightening the confidence interval for a given bandwidth. Second, more observations tend to yield a

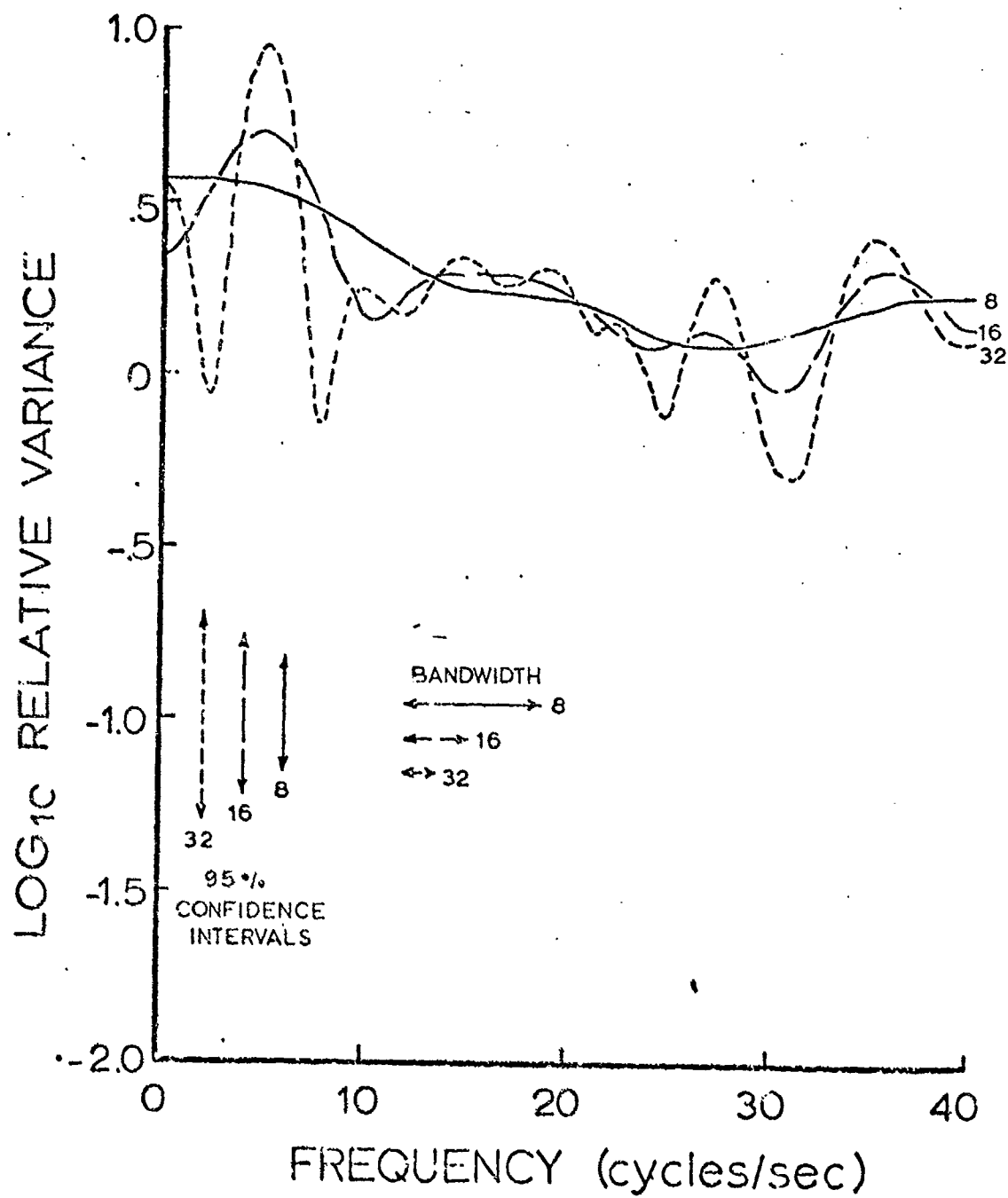
Figure 21. Spectral density function with 95% confidence erected about it. The curve labeled "8" is reproduced from Fig. 20. The dashed curves above and below this function represent the 95% confidence interval. The flat heavy black line is the theoretical spectral density function for white noise or a Gaussian process.



more stable autocorrelation function which in turn causes fewer distortions when transformed into the frequency domain. In Fig. 22 are the spectral density functions for the same cosine plus noise process, but with $N = 160$ observations. The confidence intervals are much narrower than in Fig. 20. Further, spurious peaks still occur, but to a lesser degree than before. Moreover, these false peaks are not as high as in Fig. 20, nor are they centered at the same frequencies.

At this juncture, it is appropriate to discuss the matter of optimal record length. The advantages of examining a series made up of many observations which yields stable estimates must be weighed against the ensuing disadvantages arising from the greater time and expense (both experimental and computational) that long records entail. Additionally, the process of interest may remain covariance stationary only for a short time. Thus the length of the time series chosen cannot be specified in general. It should include enough observations to provide reasonable stability and fidelity. Of course, the highest frequency of interest determines the choice of Δt . The procedure of estimating three spectral density functions from each sample time series is an empirical method suggested by Jenkins & Watts (1968) for gaining some insight into the stability of the estimates. In many practical situations (e.g., the analysis which follows) rather short series ($N = 60$ or 70) can be analyzed to determine the general shape of the

Figure 22. Spectral density functions of the cosine plus noise process estimated from autocorrelation functions which were themselves computed from a series of 160 observations.



spectral density function; however, rarely can individual peaks be resolved from so few observations, unless the process produces very stable estimates.

Application of Spectral Analysis to Session Records of Peak Force

In Chapters 3 and 4 a training session was terminated when a subject had obtained 50 reinforcements. This procedure allowed individual differences to arise in terms of the number of responses recorded for each subject during a session. Thus during Phase II the number of responses ranged from 52 to over 100. These sequences of peak force measurements were the data to which spectral analysis was applied. Since the behavior was free-operant, time between measurement was left free to vary according to the characteristics of each subject. As a result, the data cannot be expressed in terms of real time units, rather peak force is taken to be a function of ordinal position or number of the response measurement in the sequence of observations which comprise a session record. Accordingly, the frequencies of oscillation are expressed in units of cycles per response (cpr).

It was anticipated that substantial individual differences in patterns of responding would arise. Therefore, no attempt was made to average the computed spectral density functions. Because the number of observations was extremely small for a spectral analysis, several density functions were estimated for each subject using a relatively small number of lags (4 to

16). Confidence intervals were relied upon for deciding the shape of the spectrum. Further, the notion of replication was used as an adjunct to the confidence intervals in the following way: Spectral density functions for all subjects were estimated for the first two and last two sessions of Phase II. Then the functions for individual subjects on successive sessions (e.g., sessions 1 and 2) were compared visually, and similarities in the slope of the spectrum were noted.

Computations were made by a digital computer using the formulae presented previously, except f in formula (7) varied from 0 to 50. Before the autocorrelation and spectral density functions were estimated, the data were subjected to \log_{10} transformation and linear trend removal. Further, interpretation of the resulting functions was attempted only if the assumption of weak stationarity (or covariance stationarity was thought to hold.)

The covariance stationarity assumption was tested in the following way: The variance of the first half of the transformed series was compared with the second half variance. F ratios were then computed. Near equality of the variances was taken as evidence of covariance stationarity. However, significant departures suggested possible failure of the assumption. But in view of the large number of variance ratios computed, it was very likely that some significant values would be obtained. Therefore, the direction of change in variance on successive

sessions was also noted.

Of the 96 F ratios computed for the first two sessions of phase II, 12 were significant at the .05 level--a larger number than would be expected on the basis of sampling fluctuations (see Table 9). Likewise, for sessions 14 and 15 there were 24 such significant F ratios out of 96 computed. (Data for one subject were lost in a card reader malfunction). Thus there was some evidence that many of the records were not stationary. However, it will be recalled that the \log_{10} transformation was only partially successful in normalizing the data. Since the F-test is very sensitive to failure of the normality assumption (Hays, 1963), it is possible that the larger number of significant ratios resulted from non-normal nature of the transformed distributions. Nevertheless, the decision was made to adopt a very conservative criterion for covariance stationarity. Thus any subject's data displaying a significant F ratio on one of two successive sessions was treated as non-stationary. One consideration which weighed heavily in choosing a strict criterion was the fact that very short series were being analyzed--a circumstance which tends to limit the validity of spectral analytic techniques.

With respect to direction of variance change during a session, about half of the subjects increased and half decreased. In Table 9 are given the number of occurrences of each type of variance change. Both directions and degree of variance change

Table 9

Number of Subjects Displaying Each Type
of Variance Change During Phase II

Session Number	Group	Increase ¹	Decrease	No Change	Signif. at .05 Level
1	1	2	5	0	1
	2	6	2	0	1
	3	4	3	0	0
	4	4	3	0	0
	5	6	3	0	0
	6	6	4	0	3
Totals		28	20	0	5
2	1	2	5	0	1
	2	4	4	0	2
	3	4	3	1	0
	4	3	3	0	1
	5	7	2	0	0
	6	5	5	0	3
Totals		25	22	1	7
14	1	2	4	1	0
	2	5	2	0	3
	3	5	3	0	2
	4	4	3	0	3
	5	4	5	0	0
	6	6	4	0	4
Totals		26	21	1	12
15	1	2	5	0	3
	2	4	3	0	1
	3	6	2	0	0
	4	2	5	0	1
	5	3	6	0	4
	6	6	4	0	3
Totals		23	25	0	12

Notes:

1. Increase means that variance of second half was greater than the variance in the first half of the session.

were approximately equally distributed among experimental groups.

Early Conditioning in Phase II

For sessions 1 and 2 of Phase II, 37 subjects were assumed to have covariance stationary records. Only eight of these displayed spectral density functions which were substantially different from a Gaussian process on successive sessions. Interestingly, the type of non-random component was similar for all eight subjects. The spectral density functions for these animals provided evidence for an underlying high frequency component of $1/3$ to $1/2$ cycle per response. In Figs. 23 and 24 are presented the data for one of these subjects. Figure 23-A shows the peak force of response plotted as a function of ordinal position. There does seem to be a distinct tendency for the forces to "oscillate" rapidly up and down. This same pattern is again seen in the autocorrelation function (Fig. 23-B). And, as expected, the estimated spectral density function (Fig. 23-C) shows that higher frequencies account for more of the variance than do the lower frequencies. The high frequencies also dominate the pattern of peak forces emitted during session 2 (see Fig. 24-A, B, C). Estimates of the spectral density function, for this session are quite stable (Fig. 24-C): the

Figure 23-A. Peak force of response as a function of ordinal position. The data are from the first session of Phase II. This individual was in Group 4 (see Chapter 3).

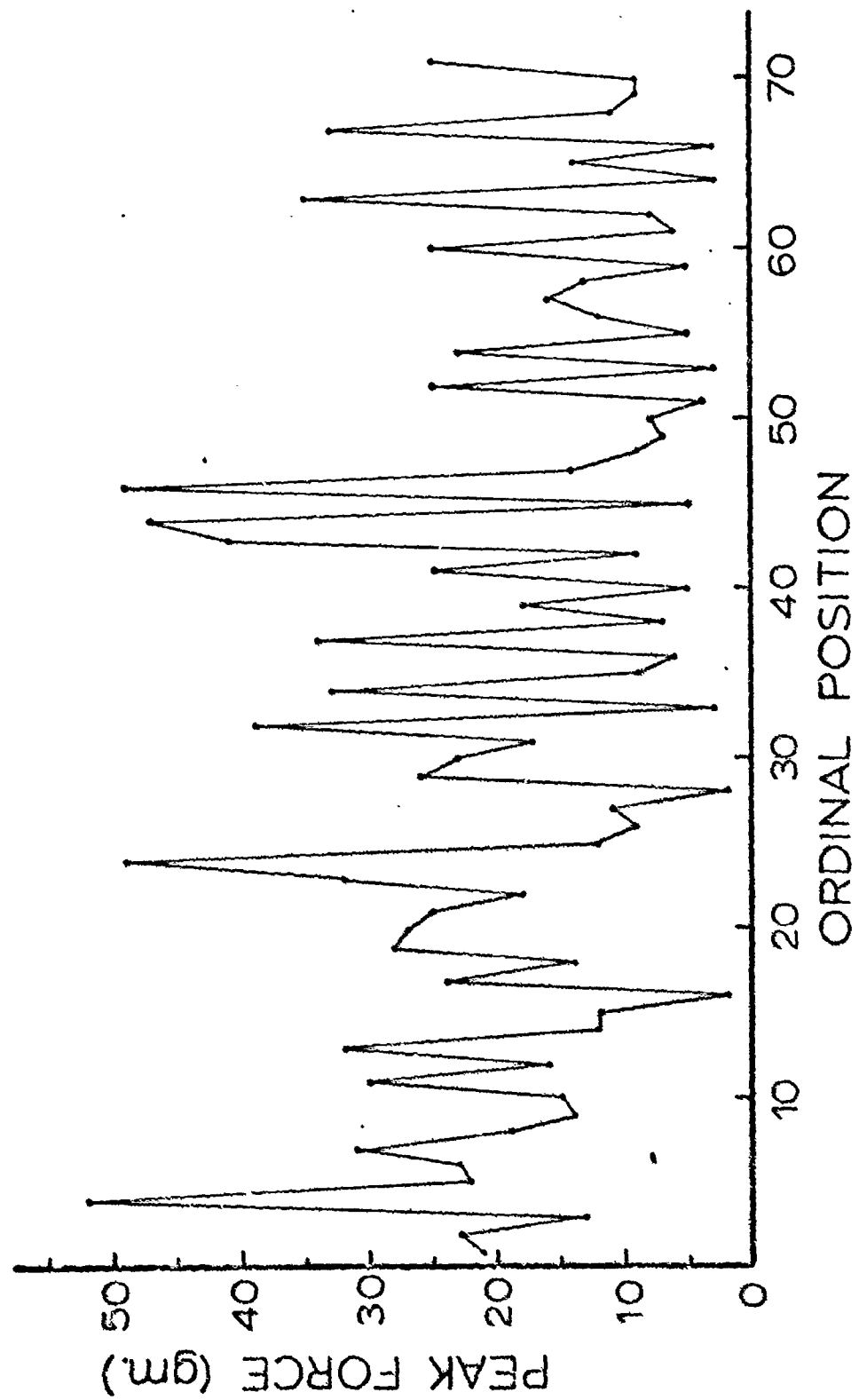


Figure 23-B. Autocorrelation function of 16 lags estimated from the data shown in Fig. 23-A. Note the relatively large negative correlation at lag 1.

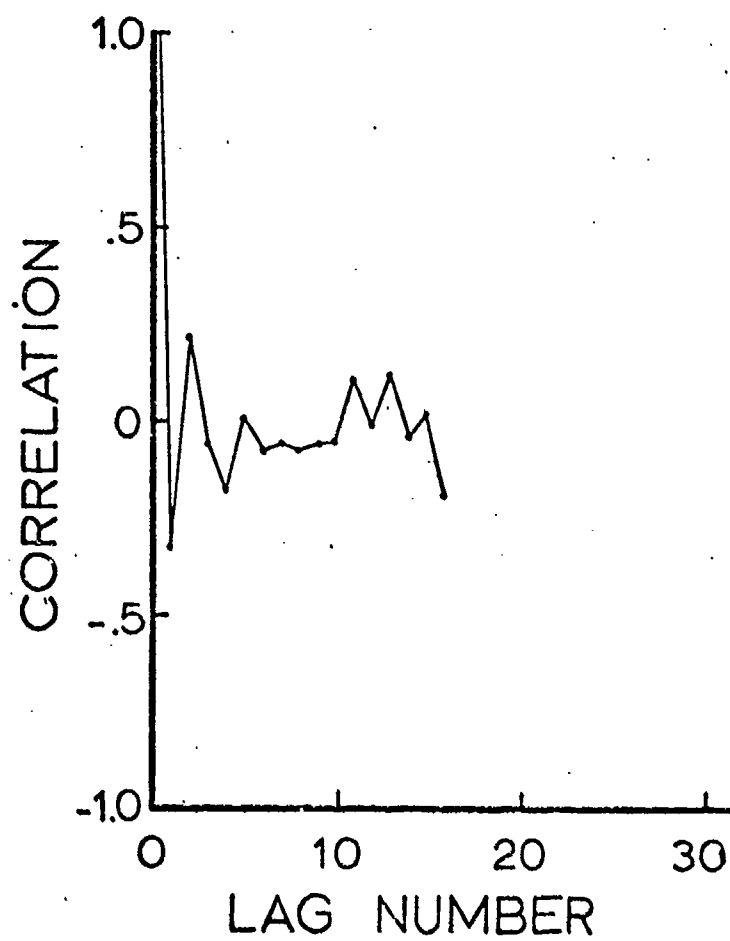


Figure 23-C. Spectral density functions for the data presented in Fig. 23-A. The ordinate is \log_{10} relative proportion of variance accounted for by the frequencies of oscillation which are marked off on the abscissa. The frequency units are cycles per response. Thus the range of frequencies extends from 0 to .5 cycles per response. For example, an oscillation which requires two responses for completion has a frequency of .5 cycles per response.

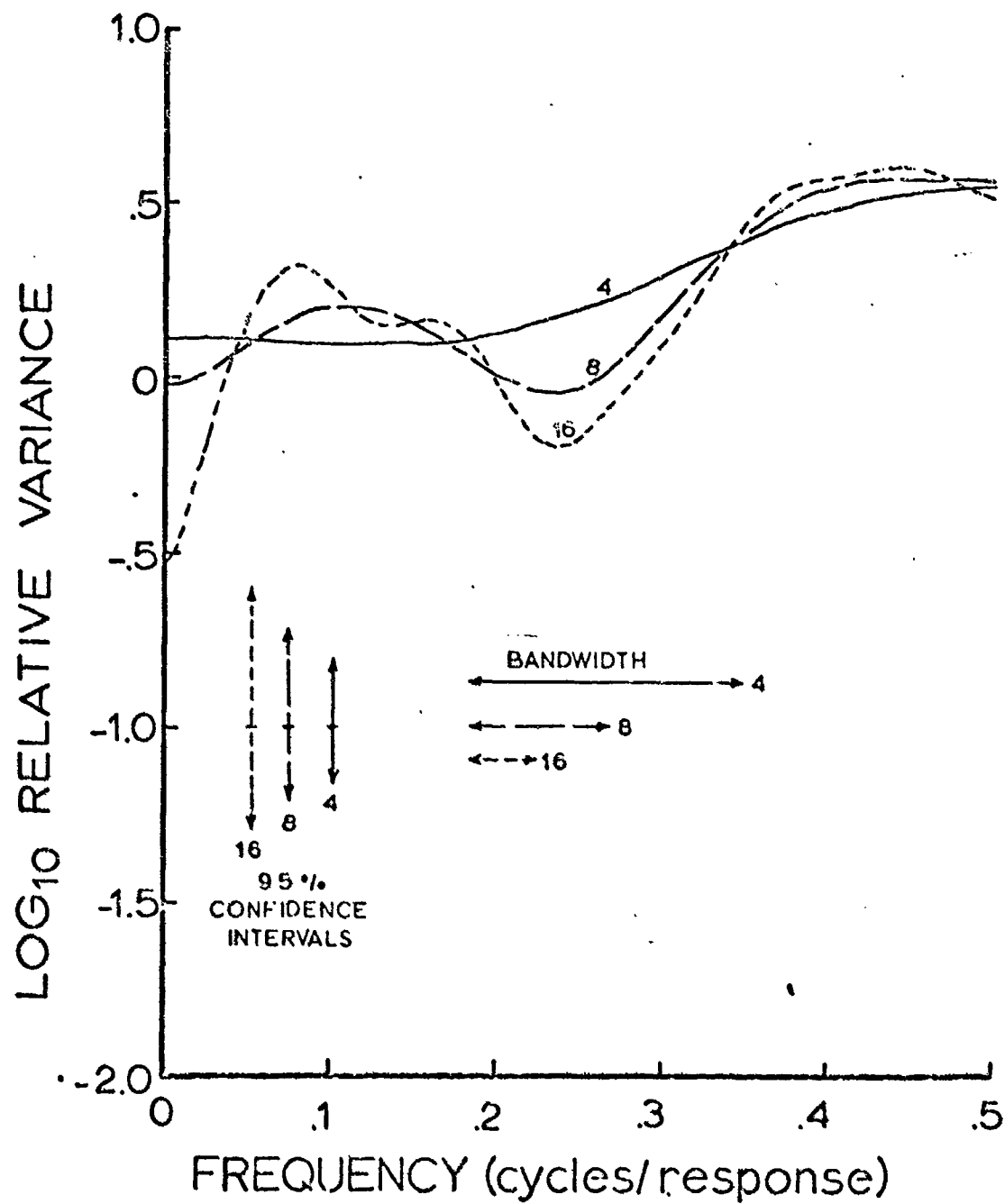


Figure 24-A. Peak force of response as a function of ordinal position for the same subject shown in Figs. 23-A, B, and C. These data were recorded in the second session of Phase II.

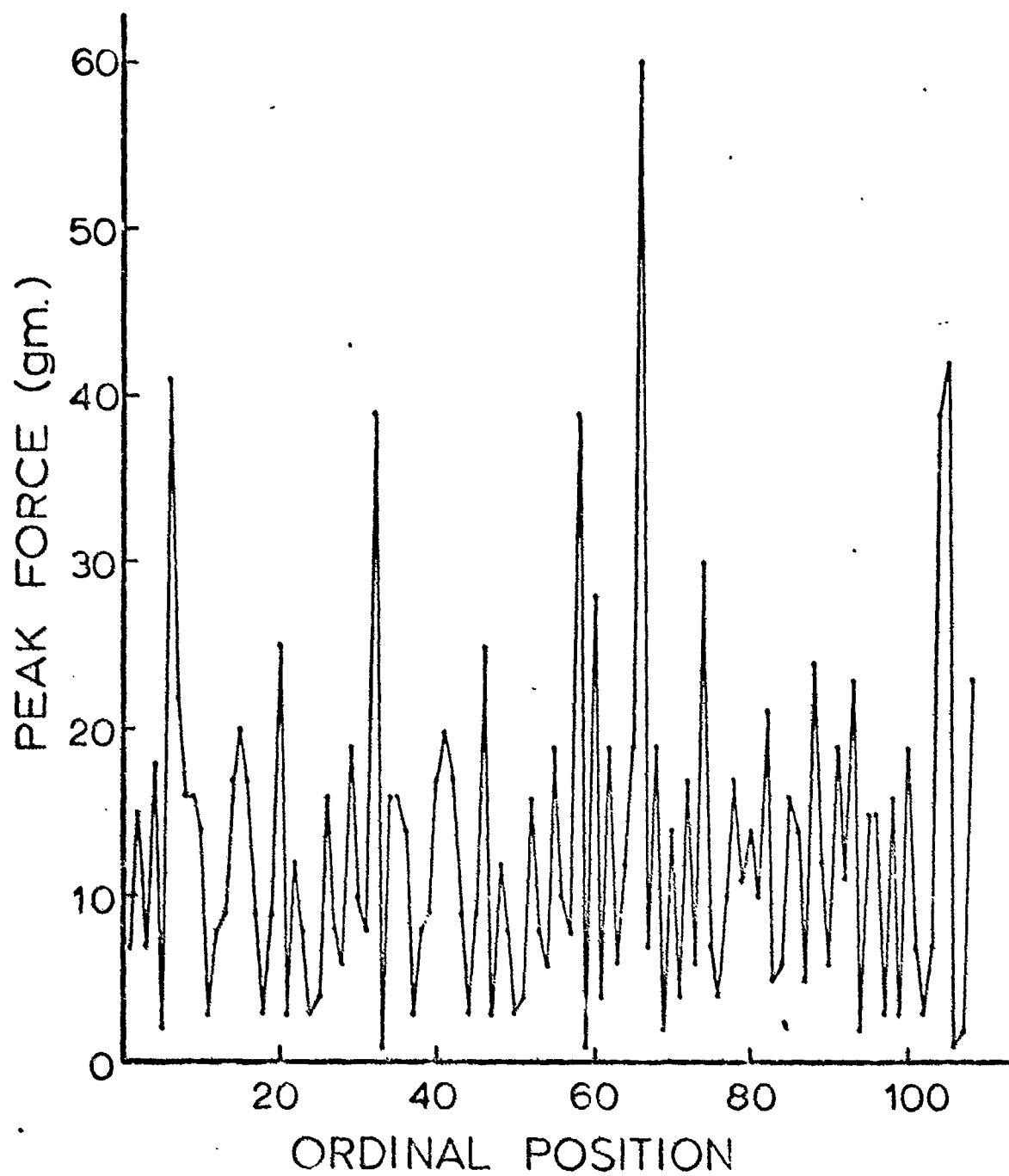


Figure 24-B. Autocorrelation function of 16 lags
estimated from the data presented in Fig. 24-A.

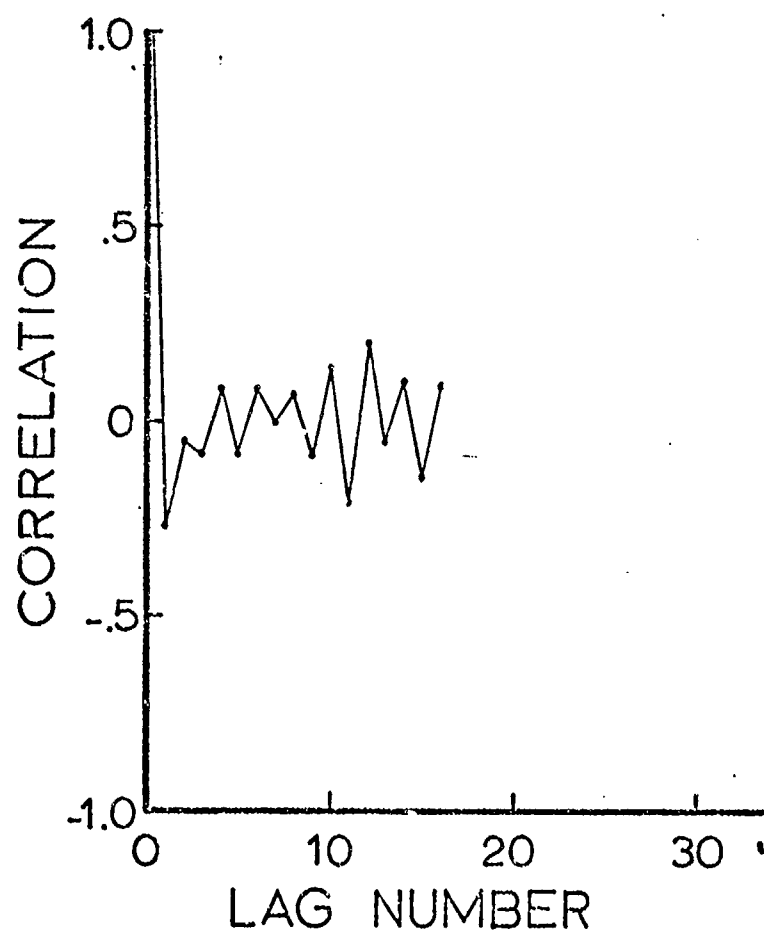
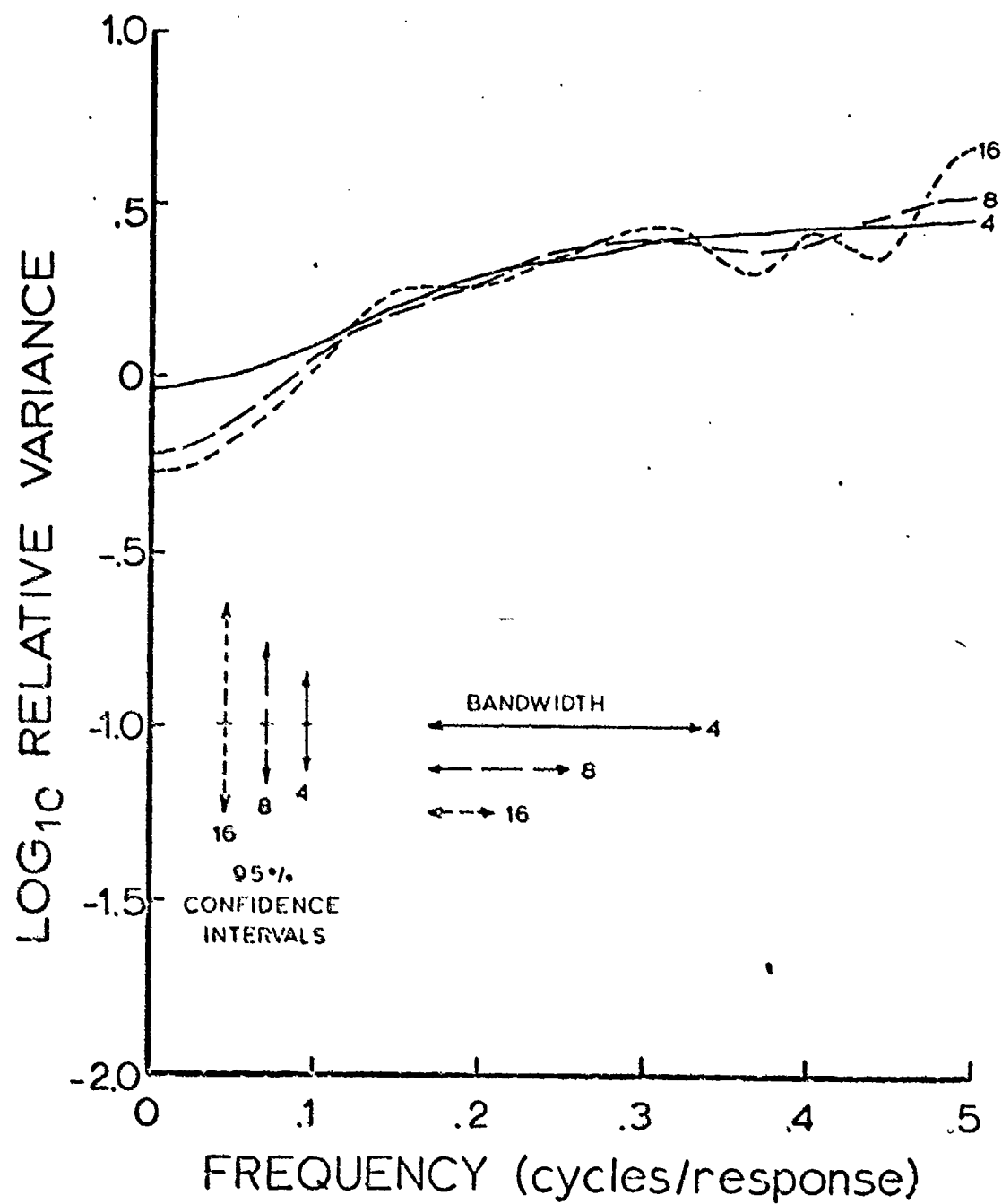


Figure 24-C. Spectral density functions computed from the session peak force data shown in Fig. 24-A. Note the positive slope of all three functions. Increasing the number of lags from 4 to 16 only slightly influences the shape of the function--a fact which indicates a high degree of stability.



shape of the function changes very little as the lag number is increased from 4 to 16. The other seven subjects displayed a replicable pattern similar in shape and magnitude to the individual just discussed. In terms of the reinforcement contingencies, of the eight subjects exhibiting a repeatable pattern all but one belonged to the groups which received the highest reinforcement densities (mg/min) i.e., Groups 3, 4, 5. However, this tendency to oscillate rapidly in F_p is not confined to the groups exposed to the force-correlated sweetness schedules, since three of the "high frequency" subjects were in Group 4. Because there were so few subjects displaying this reliable tendency to oscillate rapidly, any firm conclusion must await further experimental analysis.

The shapes of the spectral density functions shown in Fig. 23-C and Fig. 24-C are very similar to a first order autoregressive process or Markov process. This kind of theoretical process has the characteristic that the value of observation $n+1$ depends only on the value of observation n , and is independent of all other previous values. It is tempting to speculate that what occurs on one response influences only the next response, indicating, on a most conjectural level, a brief "memory" span. Without more quantitative support such suggestions, however, must remain purely speculative.

In contrast to the eight atypical subjects, (i.e., those displaying a replicable high frequency oscillation) were the remaining 29 animals, which also exhibited covariance stationary

F_p records. Spectral density functions for these animals were essentially flat, with no particular range of frequencies tending to dominate. Further, neither the slopes nor the peaks of these functions were the same on successive sessions. The data for a typical individual displaying these qualities are presented in Fig. 25 (A, B, and C) and Fig. 26 (A, B, and C). These results are compatible with the conclusion that the "pattern" of peak force for most of the animals does not depart substantially from complete randomness. This is rather surprising for early conditioning. One might have expected some kind of intrasession effect to emerge in the early sessions, but--on the whole--the data do not support this view.

Later Conditioning in Phase II

Only 27 subjects met the criterion for covariance stationarity established previously. Of these, six yielded evidence of a repeatable, non-random pattern of responding. The particular shapes of the spectral density functions for these atypical animals were quite similar to those described for the data collected early in conditioning. Further, these six subjects were approximately equally represented in each of the experimental groups. However, these six subjects were not the same individuals exhibiting non-randomness in the first two sessions.

The failure for individual differences to remain apparent throughout conditioning may become more understandable by some

Figure 25-A. Peak force as a function of ordinal position within a session. These data were gathered from an individual in Group 2 during the first session of Phase II.

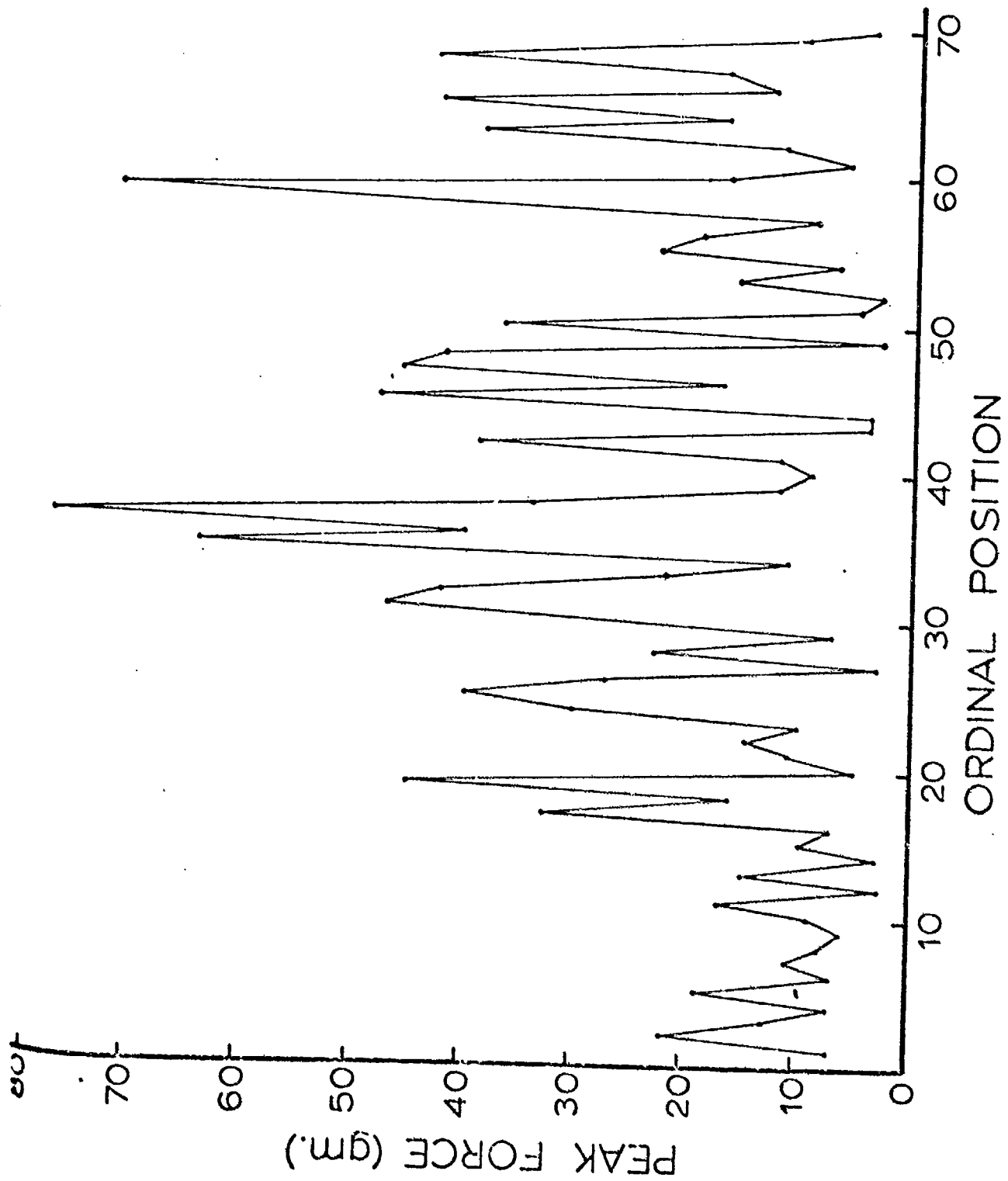


Figure 25-B. Autocorrelation function of 16 lags estimated from the data presented in Fig. 25-A.

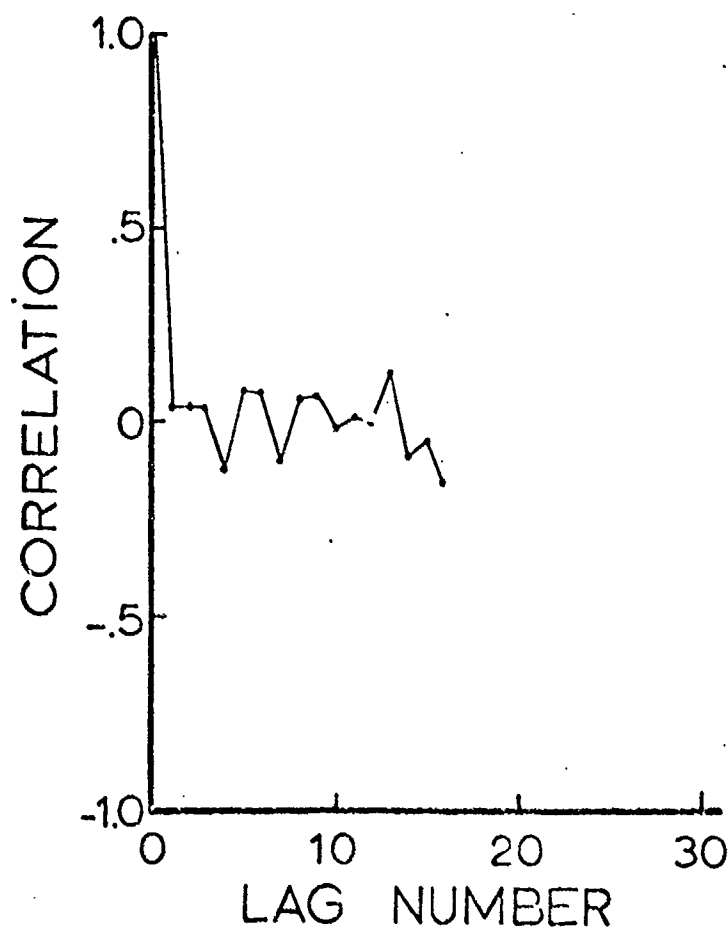


Figure 25-C. Spectral density functions obtained from the session peak force record shown in Fig. 25-A. The functions are very flat suggesting that all frequencies are approximately equally represented in the process. Compare the functions for 4 and 8 lags with the theoretical function for white noise shown in Fig. 21.

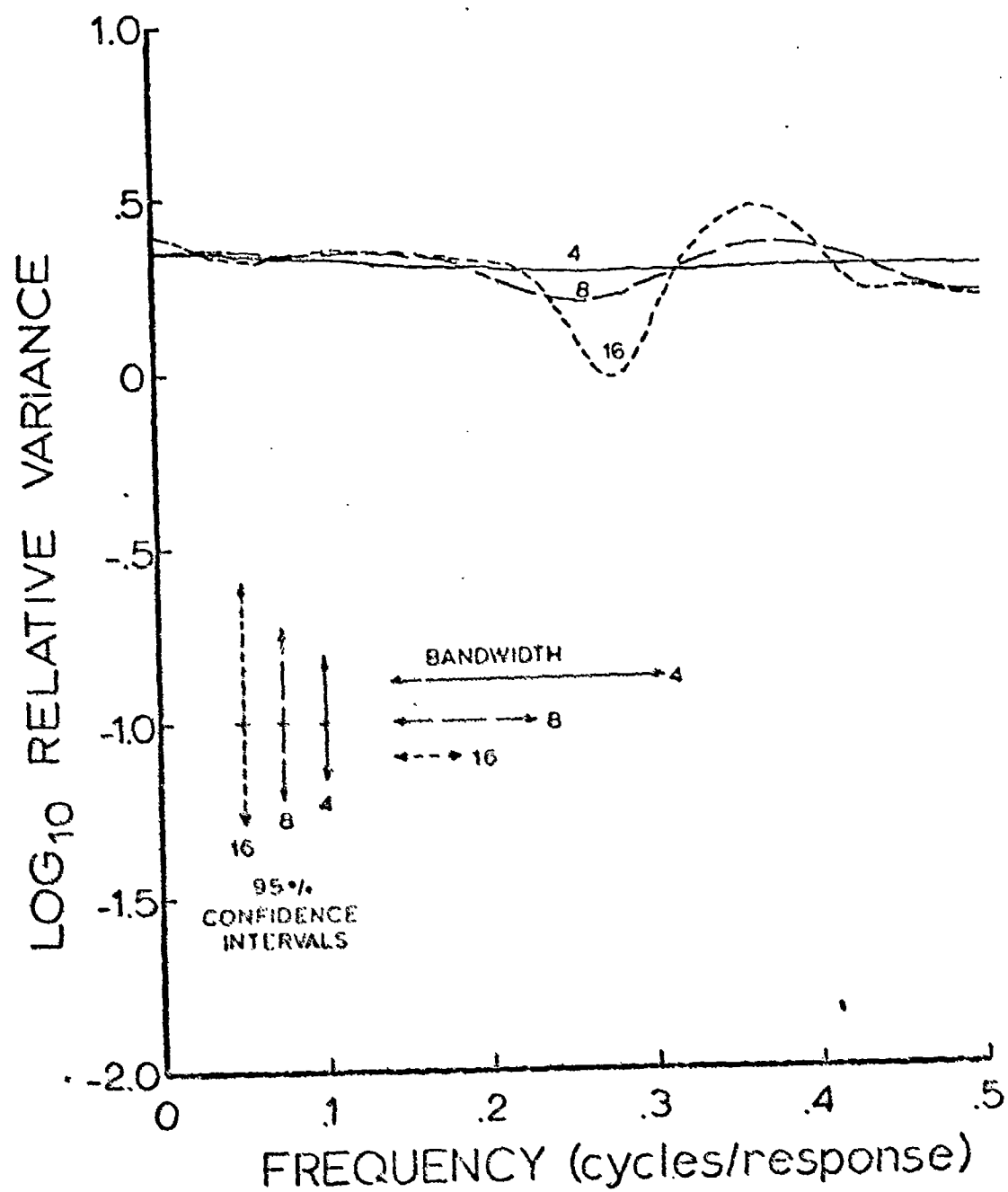


Figure 26-A. Peak force as a function of ordinal position for the second session of Phase II. This is the same individual whose data are given in Fig. 25-A.

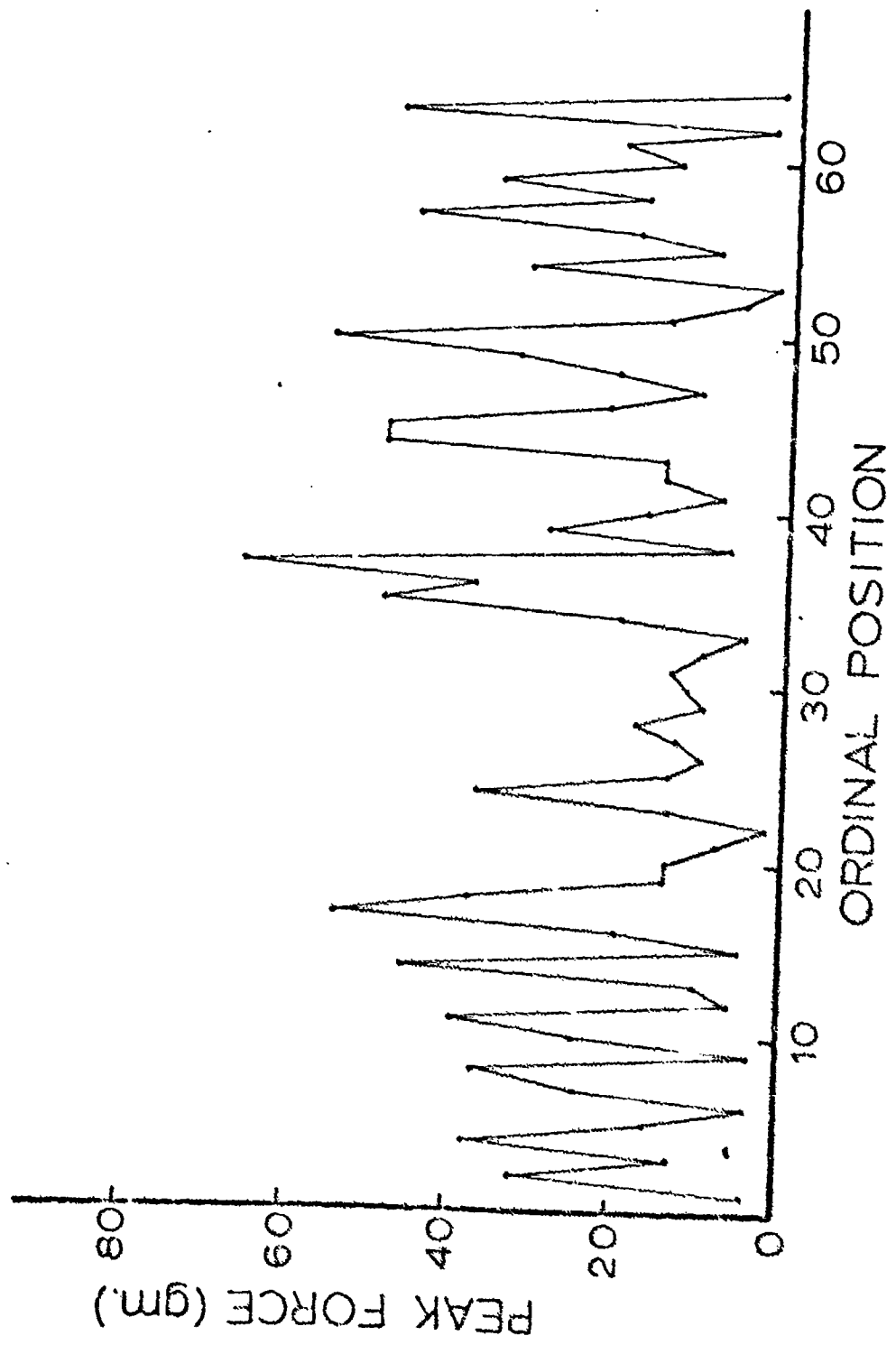


Figure 26-B. Autocorrelation function of 16 lags estimated from the data shown in Fig. 26-A.

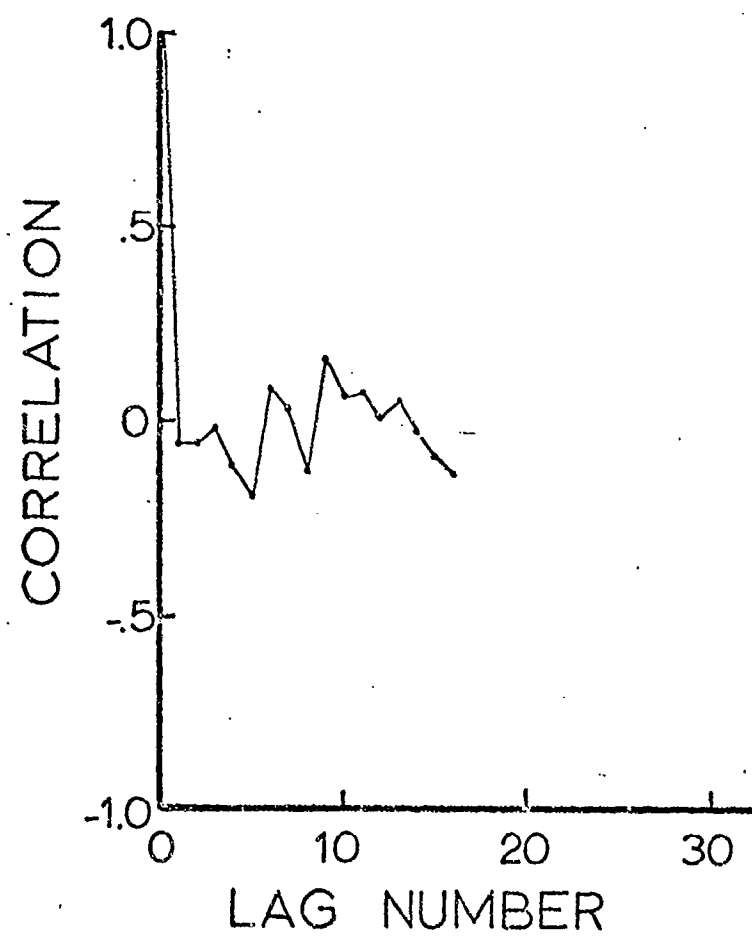
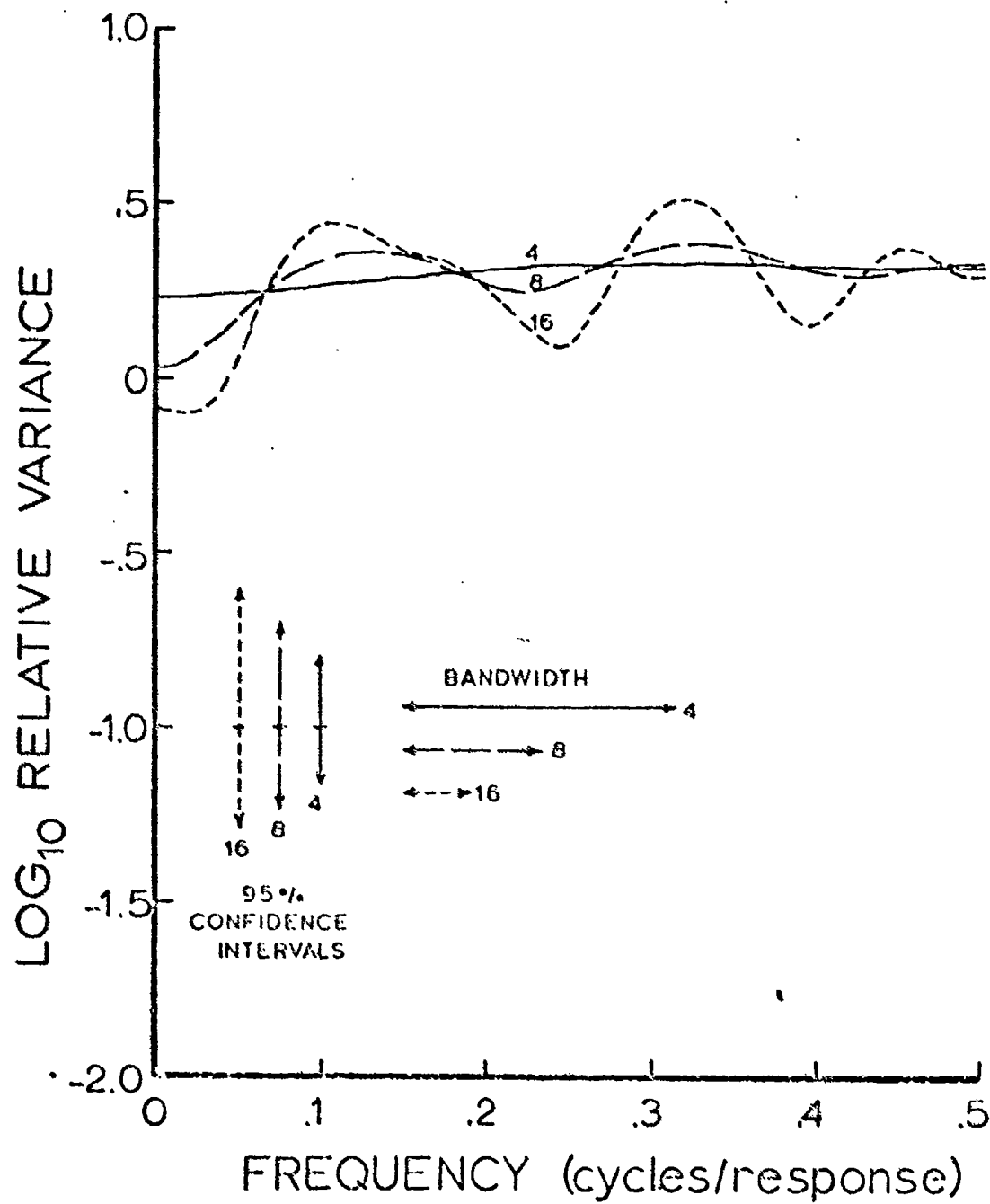


Figure 26-C. Spectral density functions for a subject of Group 2 estimated from F_p data obtained in the second session of Phase II.



additional considerations. For both early and late conditioning, many subjects which did not display repeatable patterns, nevertheless exhibited a strong high frequency component on one of the two sessions. Moreover, a large number of animals which produced non-stationary records in one session shifted to covariance stationary responding in the subsequent session, or vice versa. If one considers all the peak force records that yielded non-significant F ratios, the dominant non-random tendency emerging in the spectral density functions was in the high frequency region. It is still true, however, that the pattern of forces emitted by the large majority of subjects, during any given session, did not depart substantially from randomness. From the foregoing statements one can infer that there may be a genuine tendency for most of the animals to show rapid ups and downs in the emission of forces, but only rarely do the high frequencies dominate to the extent that they emerge as a non-random component. On the other hand, one cannot argue in the same manner for the intermediate and lower frequencies because these components never appear with any strength or regularity.

Overview of Possible Feedback Processes

The sequences of forces emitted within a given session did not display any linear trends. When examined in this way, the peak force data do not provide for a description of the supposed satiation-hunger loop. Either peak force is unresponsive to

such satiation effects, or a much longer time of responding is required before these effects can be observed.

Spectral analytic techniques suggested that there may be a high frequency (.33 to .5 cpr) oscillation, but it is relatively insignificant when compared to the pervasiveness of the random nature of the response sequences. Nevertheless, this high frequency component does provide a modicum of evidence for a reinforcement-response loop. The tendency for forces to oscillate rapidly up and down may be interpreted in the following way: The rat is exposed to successive changes in sweetness or amount (or both) that are probably discriminably different. Thus receipt of an 8.0% solution would increase the likelihood that the next response would be harder, and if a 24.0% solution was then obtained, one would expect the ensuing response to be less vigorous. This argument follows from the empirical relations between mean F_p and amount of reinforcement mentioned earlier (see DiLollo, Ensminger, & Notterman, 1965; and Notterman & Mintz, 1965). The same reasoning holds for subjects in Group 1, except only two different reinforcements are given-- 0% and 8.0%.

From a quantitative point-of-view, the results of the foregoing analyses have some important implications. First, it may be appropriate to average the spectral estimates to obtain a clearer picture of the high frequency component. Second, in future related experiments the number of reinforcements

delivered in one session can probably be increased to 75 or more without endangering the stationarity assumptions. The longer series thereby produced should provide more stable estimates of the spectral density functions. Third, the data analyzed so far show that very little information is lost by using mean F_p to describe session performance.

Chapter 6

Summary of Results and Conclusions

A number of conclusions may be based on the foregoing experimental and quantitative analyses:

1. On the average, proportional reinforcement defined exclusively in terms of amount (mg.) does not shape forces upward. This is true of continuous proportionality as well as discontinuous step-wise proportionality under a number of parametric conditions.

2. On the other hand, force proportional reinforcement, defined in terms of concentration of sucrose does substantially increase the likelihood of high force emission. Rats press harder to get sweeter rewards but do not press harder to obtain more of the same kind of reward.

3. Peak force distributions are virtually continuous and are unimodal, even for the 2-step proportional concentration groups. There is a general tendency, manifested by all the groups (1-6) for the mean and standard deviation to be highly correlated. (Though not previously mentioned, this relationship holds for the combined groups of Chapter 2 - Groups C8, P8, and P32 - where $r = .691$.)

4. Rate of responding viewed as interresponse time independently of consumption time, was not differentially influenced by the reinforcement operations, probably because of

a "floor" effect - all groups were responding about as fast as was consistent with consuming all the sucrose delivered in a single reinforcement.

5. The ratio of payoff to exertion, the gain, had very little influence on mean peak force. However, the studies did provide some evidence that higher gain values were "chosen" by most subjects, but only when high gain was paired with a low force requirement.

6. Within a given session there was no evidence for a linear trend in F_p , perhaps indicating the absence of any satiation effects.

7. Also, the sequences of responses emitted during a session showed only slight departure from randomness, in the sense that the spectral density functions were generally flat. Such non-random effects that did emerge took the form of a high frequency component (.33 to .5 cpr), indicating a tendency for F_p to display sharp ups and downs. The serial effects were distributed approximately equally among the various experimental groups. With regard to the question of constant variance within a given session, the evidence is compatible with the notion that the majority of subjects do exhibit stationary sequences of F_p .

It probably comes as no surprise that the proportional contingency between force of response and concentration of sucrose brought about more forceful responding. This finding does, however, serve to underscore the importance of the stimulus

properties of reinforcement. By way of speculation it may be suggested that the taste of the various solutions were differential cues which were essential in the process of learning to press harder.

References

- Abelson, R. P. Spectral analysis and the study of individual differences in the performance of routine repetitive tasks. Unpublished doctoral dissertation, Princeton University, 1953.
- Antonitis, J. J. Variability of response in the white rat during conditioning and succeeding extinction and reconditioning. Unpublished doctoral dissertation, Columbia University, 1950.
- Arnold, W. J. An exploratory investigation of primary response generalization. Journal of Comparative Psychology, 1945, 38, 87-102.
- Bendat, J. S. & Piersol, A. G. Measurement and analysis of random data. New York: Wiley, 1966.
- Blackman, R. B. & Tukey, J. W. The measurement of power spectra. New York: Dover, 1958.
- Brown, J. S. & Horsfall, R. B. Speed contingent reinforcement. Psychonomic Science, 1965, 3, 305-306.
- Campbell, B. A. Absolute and relative sucrose preference thresholds for hungry and satiated rats. Journal of Comparative and Physiological Psychology, 1958, 51, 795-800.
- Catania, C. A. Concurrent performances: a baseline for the study of reinforcement magnitude. Journal of the Experimental Analysis of Behavior, 1963, 6, 299-300.
- Catania, C. A. Concurrent operants. In Operant behavior: areas of research and application, W. K. Honig (Ed.).

New York: Appleton-Century-Crofts, 1966.

Chung, S. Effects of effort on response rate. Journal of the Experimental Analysis of Behavior, 1965, 8, 1-7.

Cochran, W. T., et al. What is the fast Fourier transform? IEEE Transactions on Audio and Electroacoustics, 1967, AU-15, p. 45. (See other portions of same volume.)

Collier, G. & Myers, L. The loci of reinforcement. Journal of Experimental Psychology, 1961, 61, 57-66.

Collier, G. & Siskel, M. Performance as a joint function of amount of reinforcement and interreinforcement interval. Journal of Experimental Psychology, 1959, 57, 115-120.

Crespi, L. P. Quantitative variation of incentive and performance in the white rat. American Journal of Psychology, 1942, 55, 467-517.

DiLollo, V., Ensminger, W. D., & Notterman J. M. Response force as a function of amount of reinforcement. Journal of Experimental Psychology, 1965, 70, 27-31.

Filion, R. D. L., Fowler, S. C. & Notterman, J. M. Some effects of simultaneous force-proportional positive and negative reinforcement. Journal of Experimental Psychology, 1969, 82, 267-271.

Filion, R. D. L., Fowler, S. C. & Notterman, J. M. Effort expenditure during proportionally reinforced responding. Quarterly Journal of Experimental Psychology, 1970, in press.

Fishman, G. S. Spectral methods in econometrics. Rand

Corporation, 1968.

- Guttman, N. Operant conditioning, extinction, and periodic reinforcement in relation to concentration of sucrose used as a reinforcing agent. Journal of Experimental Psychology, 1953, 46, 213-224.
- Guttman, N. Equal reinforcement values for sucrose and glucose solutions compared with equal sweetness values. Journal of Comparative and Physiological Psychology, 1954, 47, 358-361.
- Hays, W. L. Statistics for psychologists. New York: Holt, Rinehart & Winston, 1963.
- Hendry, D. P. The effect of correlated amount of reward on performance on a fixed-interval schedule of reinforcement. Journal of Comparative and Physiological Psychology, 1962, 55, 387-391.
- Hendry, D. P. & Van-Toller, C. Performance on a fixed ratio schedule with correlated amount of reward. Journal of the Experimental Analysis of Behavior, 1964, 7, 207-209.
- Herrnstein, R. J. Relative and absolute strength of response as a function of frequency of reinforcement. Journal of the Experimental Analysis of Behavior, 1961, 4, 267-272.
- Hodgman, C. D. (Ed.). Handbook of chemistry and physics. (44th ed.) Cleveland: Chemical Rubber Pub. Co., 1962.
- Hull, C. L. Principles of behavior. New York: Appleton-Century, 1943.
- Jaynes, J. The routes of science. American Scientist, 1966,

54, 94-102.

Jenkins, G. M. & Watts, D. G. Spectral analysis and its applications. San Francisco: Holden Day, 1968.

Keller, F. S. & Schoenfeld, W. N. Principles of psychology. New York: Appleton-Century-Crofts, 1950.

Kraeling, D. Analysis of amount of reward as a variable in learning. Journal of Comparative and Physiological Psychology, 1961, 54, 560-565.

Logan, F. A. A micromolar approach to behavior theory. Psychological Review, 1956, 63, 63-73.

Logan, F. A. Incentive: how the conditions of reinforcement affect the performance of rats. New Haven: Yale, 1960.

Logan, F. A. & Wagner, A. R. Reward and punishment. Boston: Allyn & Bacon, 1965.

McFarland, D. J. Control theory applied to the control of drinking in the barbery dove. Animal Behavior, 1965, 13, 478-492.

Mintz, D. E. Force of response during ratio reinforcement. Science, 1962, 138, 516-517.

Neuringer, A. J. Choice and rate of responding in the pigeon. Unpublished doctoral dissertation, Harvard University, 1967.

Notterman, J. M. & Mintz, D. E. Exteroceptive cueing of response force. Science, 1962, 135, 1070-1071.

Notterman, J. M. & Mintz, D. E. Dynamics of response. New York: Wiley, 1965.

- Notterman, J. M. Behavior: a systematic approach. New York: Random House, 1970.
- Pfaffman, C., Young, P. T., Dethier, V. G., Richter, C. P., & Stellar, E. The preparation of solutions for research in chemoreception and food acceptance. Journal of Comparative and Physiological Psychology, 1954, 47, 93-96.
- Reynolds, G. S. Behavioral contrast. Journal of the Experimental Analysis of Behavior, 1961, 4, 57-71.
- Sheffield, F. D. New evidence on the drive-induction theory of reinforcement. In R. N. Haber (Ed.), Current research in motivation. New York: Holt, Rinehart & Winston, 1966.
- Shettleworth, S. & Nevin, J. D. Relative rate of response and relative magnitude of reinforcement in multiple schedules. Journal of the Experimental Analysis of Behavior, 1965, 8, 199-202.
- Skinner, B. F. The behavior of organisms: an experimental analysis. New York: Appleton-Century, 1938.
- Smith, K. U. Delayed sensory feedback and behavior. Philadelphia: W. B. Saunders, 1962.
- Smith, M. & Duffy, M. Evidence for dual reinforcing effect of sugar. Journal of Comparative and Physiological Psychology, 1957, 50, 242-247.
- Stellar, E. & Hill, J. H. The rats rate of drinking as a function of water deprivation. Journal of Comparative and Physiological Psychology, 1952, 45, 96-102.

- Tarpy, R. M. The reinforcement difference limen (RDL) for delay in shock escape. Unpublished doctoral dissertation, Princeton University, 1967.
- Trotter, J. R. The physical properties of bar pressing behavior and the problem of reactive inhibition. Quarterly Journal of Experimental Psychology, 1956, 8, 97-106.
- Valenstein, E. S. & Weber, M. L. Potentiation of insulin coma by saccharin. Journal of Comparative and Physiological Psychology, 1965, 60, 443-446.
- Wiener, N. Cybernetics or control and communication in the animal and the machine. New York: Wiley, 1948.
- Wilcoxon, F. & Wilcox, R. A. Some rapid approximate statistical techniques. Pearl River, New York: Lederle Labs., 1964.
- Weiss, B., Laties, V. G., Siegel, L. & Goldstein, D. A computer analysis of serial interactions in spaced responding. Journal of the Experimental Analysis of Behavior, 1966, 9, 619-626.
- Zeaman, D. Response latency as a function of amount of reinforcement. Journal of Experimental Psychology, 1949, 39, 466-483.